

MICROBIAL AND ENZYME ACTIVITIES OF SALINE AND SODIC SOILS

Kripal Singh*

*Division of Agronomy and Soil Science, CSIR-Central Institute of Medicinal and Aromatic Plants, Lucknow-226015, Uttar Pradesh, India**Received: 14 October 2014; Revised: 27 March 2015; Accepted: 27 March 2015*

ABSTRACT

Salinization and sodication are abiotic soil factors, important hazards to soil fertility and consequently affect the crop production. Soil salinization is of great concern for irrigated agriculture in arid and semi-arid regions of the world; sodicity is characterized by an excessively high concentration of sodium (Na) in their cation exchange system. In recent times, attention has been turned to study the impacts of these factors (salinity and sodicity) on soil microbial activities. Microbial activities play central role in degradation and decomposition of soil organic matter, mineralization of nutrients and stabilization of soil aggregates. To understand the ecology of soil system, therefore, it is important to be conversant with the soil microbial activities, which show quick response to little change in the soil environment. Microbial activities (generally measured as C–N dynamics, soil respiration–basal respiration, or CO₂ emission), microbial abundance, microbial biomass, quotients (microbial and metabolic) and microbial community structure, and soil enzymes have been considered as potential indicators to assess the severity of the land degradation and the effectiveness of land use management. Therefore, it is important to synthesize the available information regarding microbial activities in use and management of salt-affected soils. The reclamation and management of such soils and their physico-chemical properties have been reviewed well in the literature. In this review, an attempt has been made to compile the current knowledge about the effects of soil salinization and sodication on microbial and enzyme activities and identify research gaps for future research. Copyright © 2015 John Wiley & Sons, Ltd.

KEY WORDS: exchangeable sodium percentage; microorganisms; microbial activities; salt-affected soils; soil enzymes

INTRODUCTION

Deterioration of soil quality by soil salinization and sodication is a global problem. Salt affected soils, are commonly occurring in arid and semi-arid regions (Pandey *et al.*, 2011; Ferreira *et al.*, 2015) and gradually spreading in various regions of the world (Lambers, 2003). Salt-affected soils occupy approximately 3% of the world's total geographical area; 402 and 434 million hectare (Mha) lands are classified as saline and sodic, respectively. There are 137 Mha (5% of the total geographical area) sodic soils in the Asia-Pacific region (Shukla *et al.*, 2011). Furthermore, extensive agricultural practices with poor irrigation and drainage practices may lead to manifold increase in this area in the forthcoming decades (Lambers, 2003). Salinization and sodication affect physico-chemical, biological, and biochemical properties of soil (Gill *et al.*, 2008; Rietz & Haynes, 2003; Singh *et al.*, 2013b, 2013c), and affecting the crop productivity to a significant extent (Gill *et al.*, 2009). Despite the extensive studies on the effects of salinity and sodicity on soil properties (Qadir *et al.*, 2007) and crop growth, little is known about their possible effects on soil microbial activities. Soil microbial activities (SMAs) are considered as key players in the formation of soil structure (Elliot, 1986; García-Orenes *et al.*, 2010), biodegradation of organic matter (Quails & Raines, 1992), nutrient cycling,

and energy transformation (Coleman *et al.*, 1985); therefore, their understanding in salt-affected soils is of paramount importance. The effects of fluctuations in electrical conductivity (EC; salt solutions: salinization) and exchangeable sodium percentage (ESP) or sodium adsorption ratio (SAR) (sodication) on microbial activities have been examined by several workers. Both positive and negative effects were observed in these studies with respect to salinity and sodicity, and therefore, reconciliation of proper mechanisms is yet to be resolved. The reduced and/or altered microbial activities in saline and sodic soils are likely either due to direct toxic effects of salts on microbial communities (Rietz & Haynes, 2003) or the salinity and sodicity may exert toxic effects on vegetation (crop, grass, and tree) (Wong *et al.*, 2010), which in turn, leading to decreased organic matter inputs (crop residue, litter, and fine roots) in the soil and, consequently, significant decrease in microbial activities (Singh *et al.*, 2015).

Two contrasting procedures are found in saline and sodic soils that affect soil properties (Sumner, 1993; Sumner *et al.*, 1998; Wong *et al.*, 2008). First is decreasing water availability (less osmotic potential) of the soil solution with increasing salinity and second is increasing mineralization of organic matter (carbon loss) with increasing sodicity (Rengasamy, 2006a, 2008; Wong *et al.*, 2008, 2010). Changes in soil chemical properties and osmotic potentials due to fluctuations in salinity are potential reasons affecting the microbial growth and activities (Wong *et al.*, 2010; Setia *et al.*, 2011a; Guénon *et al.*, 2013). The most notable is exosmosis or dehydration (Rengasamy, 2006b, 2008).

*Correspondence to: K. Singh, Division of Agronomy and Soil Science, CSIR-Central Institute of Medicinal and Aromatic Plants, Picnic Spot Road, Lucknow-226015, Uttar Pradesh, India.
E-mail: kripalsingh04@gmail.com

However, the accumulation of osmolytes in microbial cells enhances salt tolerance ability of microbes (Hagemann, 2011; Asghar *et al.*, 2012) to combat with low osmotic and metric potentials in the soil solution. On the other hand, in sodic soils, the available soil organic matter (SOM) is free from physical protection (poor aggregation) and undergoes for higher biological mineralization (Abiven *et al.*, 2009; Wiesmeier *et al.*, 2012). Higher accessibility (higher mineralization) of SOM for microbial decay in sodic soil may further deteriorates the fertility and physical stability of the soil (Nelson & Oades, 1998; Wong *et al.*, 2010; Fterich *et al.*, 2014). At high sodicity, availability of organic matter and metabolic energy, required for microbial assimilation, are reduced consequently; microbial cell lyses takes place and soil becomes poor in microbial activities.

Indeed, several comprehensive reviews, dealing with the effects of salinization and sodication on soil physico-chemical properties, carbon-nitrogen dynamics, and mechanisms of remediation of salt stress (Sumner, 1993, 1995; Qadir *et al.*, 2007; Dendooven *et al.*, 2010; Wong *et al.*, 2010), are available, but none has included microbial and enzyme activities. The objective is to review the literature, provide facts, concepts, and mechanisms of microbial and enzyme activities in salt-affected soils as well as to find out knowledge gaps for directing the future researches to understand the microbiology of salt-affected soils.

SALINE AND SODIC SOILS

Soils with high concentration of salts (EC), high pH, ESP, and SAR are collectively called as salt-affected soils (Soil Salinity Staff, 1954; Qadir *et al.*, 2007). In general, first soil salinization takes place, and then saline soils become sodic as Na replaces Ca and Mg from the cation exchange sites that causes dispersion of clay particles (Sumner, 1993) and, thereby, increases oxygen stress in the soils (Richards, 1954; Sumner, 1993; Naidu & Rengasamy, 1995). Sodic soils contain high concentrations of sodium carbonate (Na_2CO_3), sodium bicarbonate (NaHCO_3), and sodium chloride (Abrol & Bhumbla, 1971). Sodic soils generally have poor physical properties, with low water permeability (Qadir *et al.*, 2007). Sodicity has substantial effects on soil physical properties, causing deterioration of soil structure because of change in slaking and dispersion behavior of clay minerals upon wetting and swelling, crusting, and hardsetting on drying (Sumner, 1993; Qadir *et al.*, 2007; Wong, 2007; Wang *et al.*, 2015). This affects permeability, infiltration, and hydraulic conductivity of soils. These soils can develop naturally from saline soils, with their development related to the underlying parent material, climatic change, or as a result of leaching of salts from a saline soil (Wong, 2007). Sodic soils do not sustain significant vegetation cover (Singh *et al.*, 2013a), therefore, receive less organic matter inputs and consequently have lower organic carbon (Wong *et al.*, 2008). Low organic-matter input and high Na stress enhance the mineralization of meager quantity of inherent

organic matter (Nelson *et al.*, 1998) and induce aggregate destruction (Abiven *et al.*, 2009). Sodic soils with poor aggregate stability provide inadequate protection to the SOM. Readers interested in details of clay behavior (swelling, slaking, dispersion, and flocculation); osmotic potentials; and levels of pH, EC, ESP, and SAR in saline and sodic soils are referred to other reviews (Richards, 1954; Sumner, 1993; Naidu & Rengasamy, 1995; Nelson *et al.*, 1998; Qadir *et al.*, 2007).

Saline soils with high concentrations of salts that had its adverse effect on nutrient availability causing a pseudo-nutrient deficiency in the soil water to crops and trees. Saline soils showed good physical properties having fine particles bound with organic matter and form macro-aggregates. Furthermore, this causes flocculation that is beneficial for crop root growth (Nelson *et al.*, 1997; Nelson & Oades, 1998; Wong, 2007). Rietz & Haynes (2003) stated that soils with high electrolyte concentration are categorized as saline, but these are physically stable with greater aggregate stability, water infiltration rate, clay flocculation, and less density. Saline soils under agricultural practices receive organic inputs as crop residues, but poor quality of irrigation water and extensive chemical fertilization lead to salinization.

MICROBIAL ACTIVITIES IN SALINE AND SODIC SOILS

Microbial activities can be determined by decomposition of SOM (Rietz & Haynes, 2003), release (mineralization) of nutrients (N, P, and S) (Nelson *et al.*, 1998), carbon dioxide (CO_2) emission, and transfer of C from SOM to microbial biomass (Wong *et al.*, 2010; Balota *et al.*, 2013; Campos *et al.*, 2013). The important parameters used to explain soil microbial activities under various stresses are describes in Table I. These activities are dependent on many factors including both biotic and abiotic (Yuan *et al.*, 2007; Egamberdieva *et al.*, 2009). In general, these activities are likely to be optimum in moist neutral (pH around 7) soils at high temperature with adequate organic matter in comparison with cool, dry, and alkaline or acidic soils (Rukshana *et al.*, 2012). The increased salt content (saline soils) and decreased structural stability (sodic soils) along with other chemical alterations affect soil quality in many different ways (Figure 1). Therefore, it would be interesting to relate microbial activities with changes in salinity (EC and water content), sodicity (ESP, SAR, pH, and clay mineralogy), and quality and quantity of SOM.

Soil Respiration (CO_2 emission)/ Carbon Mineralization in Saline and Sodic Soils

The SOM decomposition and the magnitude of carbon dioxide (CO_2) emission [soil respiration (SR)] from soil are affected by salinity and sodicity (Wong *et al.*, 2008; Dendooven *et al.*, 2010). However, this might depend on the quality and quantity of organic matter (Nelson & Oades,

Table I. Description of microbial activities used to elicit the effects of salinity and sodicity

Microbial activity	Description	Reference
Soil respiration (CO ₂ emission)/ basal soil respiration	Soil respiration (SR) refers to the emission of carbon dioxide (CO ₂) during respiration soil organisms (microbes and fauna) as well as plant roots. SR, as a key factor influencing the dynamic change of CO ₂ concentration in atmosphere, is the biggest carbon efflux process after photosynthesis in the terrestrial ecosystem.	Davidson <i>et al.</i> (2006), & Wang & Fang (2009)
Soil microbial biomass (SMB)	Soil microbial biomass is a measure of the mass of the living component of soil organic matter. This SMB is responsible for decomposition of plant and animal residues and soil organic matter to release CO ₂ and plant available nutrients.	Anderson & Domsch (2010)
Microbial quotient (C _{mic} /C _{org})	The microbial quotient is the ratio of the SMB-C to SOC (C _{mic} /C _{org}) and indicates the ratio of the living fraction of SOC relative to the non-living fraction.	Anderson & Domsch (1993)
Metabolic quotient (qCO ₂)	The metabolic quotient (qCO ₂), also known as the respiratory quotient, is frequently used to determine stress in the microbial population (Anderson & Domsch, 1993) and measures the ratio of soil respiration to the SMB.	Anderson & Domsch (1993)
Soil enzyme activities	Soil enzymes play key biochemical processes in the soil system to control all processes involved in decomposition of organic matter and nutrient cycling. They have been recognized as proximate agents for mineralization of organic matter. Different intracellular and extracellular enzymatic components contribute to the overall enzymatic activity of soils.	Sinsabaugh <i>et al.</i> (2008), Yao <i>et al.</i> (2009) Gianfreda & Rao, 2011; Nannipieri <i>et al.</i> , 2012

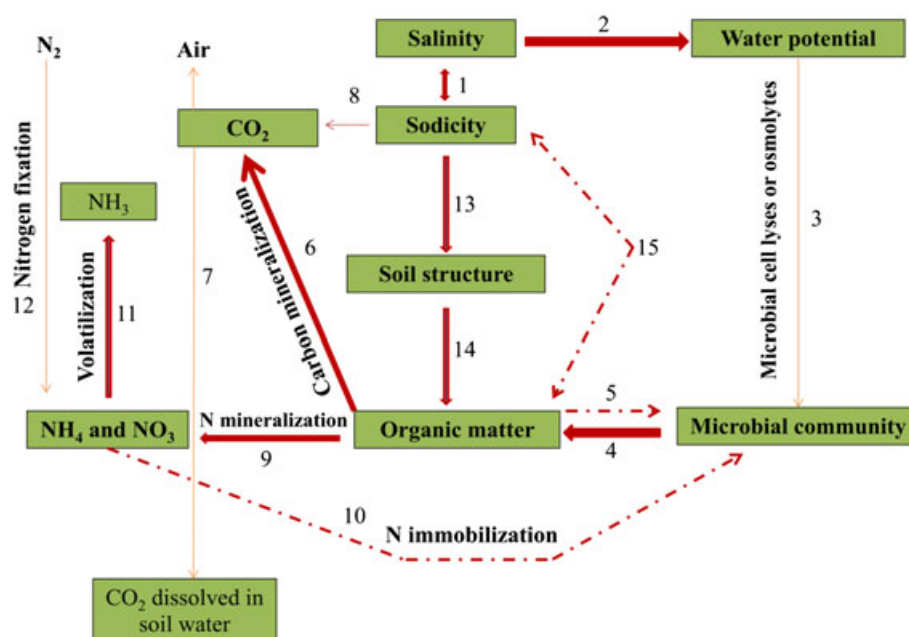


Figure 1. 1: Salinity and sodicity may exist together in soil as sodicity represent combined effects of salinity (EC) and sodicity (ESP). 2: Increase in salinity has its osmotic influences. 3: Osmotic influences cause microbial cell lyses or tolerant microbes can accumulate cell solute as osmolytes. 4: Altered microbial community affects decomposition of organic matter. 5: Addition of organic residues can stimulate the microbial biomass and activities and lighten salinity stress. 6: Increase in salinity enhances CO₂ emission because fewer microbes respire more and decompose readily available organic molecules under salinity stress. 7: CO₂ produced by microorganisms may be dissolved in the soil solution, thus underestimating the actual CO₂ evolution. 8: Dissolution of CaCO₃, available in sodic soils in excess, form CO₂, thereby leading to an overestimation of CO₂ emission. 9: Salinity affects N-mineralization through its direct effect on bacteria that produces ammonia from organic matter. 10: Increase in microbial biomass due to addition of organic residues (at 5) may immobilize inorganic N and reduce the availability of soil inorganic N. 11: Ammonia may be lost through volatilization. 12: There may be an increase in inorganic N due to fixation of atmospheric N. 13: Sodicity affects soil structure (size, shape, and arrangements of particles and pores) and behavior (slaking, dispersion and swelling). 14: This structural change in sodic soil facilitates the accessibility of organic matter for microbial decomposition. 15: Soil organic matter can affect the sodicity, and sodicity also influence soil organic matter. EC, electrical conductivity; ESP, exchangeable sodium percentage. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

1998), level of salinity and sodicity in soil (Pathak & Rao, 1998; Rietz & Haynes, 2003; Tejada *et al.*, 2006), type of salt present or added during incubation study (Li *et al.*,

2012), interaction of organic matter and microorganisms with clay mineral surface (Nelson *et al.*, 1997), and soil structure.

CO₂ Emission or C Mineralization in Saline Soils

Soil salinity is developed by a relatively high electrolyte concentration of different salts, especially, NaCl and CaCl₂, in soil solution. An increase in salt concentration results in less available water for microbial and plant growth. Salinity, beyond tolerance of microbial fauna and plants, causes death of microbial cells and degradation of plant tissues because of dehydration, toxicity to soil enzymes, and inhibits other soil processes. The reduction in microbial population and organic inputs affect decomposition process and availability of essential plant nutrients and, thereby, plant productivity. Simultaneously, under salinity stress, microbial fauna try to acclimatize with changing environment and take energy from easily decomposable organic substrates that are produced because of death of microbial cells and plant tissues, and other available labile organic molecules. These microbes increase mineralization of organic substrates, evolve more CO₂, and get energy for their own sustenance. This shift in microbial activities is up to limited level of salinity as an adaptation mechanism beyond that salinity would always be detrimental to microbial activities. Fluctuations in salinity in field conditions depend on irrigation water quality, irrigation frequency, nature of crop (deep rooted or shallow rooted) being cultivated, duration of rainy and hot seasons, field application of organic and chemical fertilizers, and other abiotic factors. Most of the research carried out to know the impact of salinity on microbial activities (C and N mineralization) was based on incubation studies. In these studies, different salts in various concentrations and organic matter (residues or compost or litter), either alone or in combination, were applied to non-saline soils. This artificially created salinity may or may not be an actual factor for changes in microbial activities especially at early stages of incubation study and may not be that much similar to natural field conditions (Macci *et al.*, 2013).

Factors affecting CO₂ emission from saline and saline-sodic soils have been correlated with soil properties including, osmotic potential and sodium adsorption ration (Setia *et al.*, 2010; Setia *et al.*, 2011b; Setia *et al.*, 2011c), soil texture (Chowdhury *et al.*, 2011c; Mavi *et al.*, 2012) and water content (Setia *et al.*, 2011a), soil organic carbon stocks (Setia *et al.*, 2012a), and residue composition and water potential (Setia *et al.*, 2012b; Setia & Marschner, 2013a; Setia & Marschner, 2013b). Several other researchers have also investigated the effect of salinity and sodicity on SR (CO₂ evolution) in laboratory (Pathak & Rao, 1998; Beltrán-Hernández *et al.*, 2007; Wong *et al.*, 2008, 2009) and field studies (Chander *et al.*, 1994; Rietz & Haynes, 2003; Yuan *et al.*, 2007; Singh *et al.*, 2012a). In all these studies, when salinity and sodicity have been induced, results were rather contradictory; both increase (Nelson *et al.*, 1996; Wong *et al.*, 2008, 2010) and decrease (Pathak & Rao, 1998) in SR have been reported. It seems that SR (CO₂ emission) besides salinity and sodicity depends on integrated effects of anthropogenic and environmental factors in a complex phenomenon.

An increase in salinity up to an EC of 5 dS m⁻¹ in the silty loam soil either with NaCl or CaCl₂ has no significant differences between two salts on SR (Setia *et al.*, 2010). Earlier study (Agarwal *et al.*, 1971) indicates that Ca⁺⁺ enhances the microbial metabolic activities, while from the later study, (Setia *et al.*, 2010) it seems that Na⁺ and Ca⁺⁺ did not differ in their toxicity to SMAs. Because SR is the result of CO₂ produced from decomposition of SOM due to microbial action and root respiration, we may not differentiate the impacts individually. Setia *et al.* (2010) argued that values of CO₂ released are not always accurate as some of CO₂ may be retained in the soil water and some may come as a result of SOM decomposition. Thus, there is respective chance of underestimation as well as overestimation CO₂ evolution.

Yuan *et al.* (2007) determined lower CO₂ emission in saline soils with highest organic carbon content in comparison with non-saline soils. This may be explained with two ways. First, organic matter is less available for microbial decomposition because of good aggregation in saline soils. Second, if this value of CO₂ is similar to other saline soils in which soil organic carbon (SOC) is less, then certainly, the salinity stress affects CO₂ emission. Setia & Marschner (2013a) reported inconsistent response in CO₂ emission in saline soils with effect of wheat and pea residues; they postulate that, in saline soils, type of residue did not affect SR, and in non-saline soil, the decrease in respiration with increasing salinity was affected by type of residue. The influence of residue on SR may be diluted under stress conditions irrespective of the quality of substrate. However, in case of non-saline soils, residue may affect the SR as no other stress will be able to dilute its affect. This may also depend on type, quantity, chemistry, and moisture content of added residue. Moist residue with less C:N ratio can decompose easily than dry with high C:N ratio. The concentration and type of organic carbon (particulate organic carbon and humus-carbon) and clay minerals are also influenced the CO₂ emission to different magnitudes whether soil is saline or not (Setia *et al.*, 2011b). The high salt concentration and high water in saline and non-saline soils will influence microbial activities differently. If the water content are relatively higher in saline soils, the high salt concentration strongly reduces microbial activities (Setia & Marschner, 2013b). The amendment of such soils with organic residue enhances their subsequent mineralization with a related increase in CO₂ emission and soil aeration (Muhammad *et al.*, 2007) probably because of stimulus in their enzymatic activities (Lakhdar *et al.*, 2009). The effect of different amounts of mature-wheat residue on SR in saline environment along with addition of NaCl was investigated by Setia *et al.* (2010). SR was influenced at all residue addition rates; however, it was more pronounced at low residue rates. The small increase in microbial biomass at low residue addition rates was unable to decompose the residues at high rates and/or the low density of residues in the soil resulted in spatial separation of microbes and substrates (Setia *et al.*, 2010).

The CO₂ flux was lowest in saline soils in comparison with peat, non-calcareous, terrace, and acidic sulfate soils

after addition of wheat, mungbean, and poultry manure. Loss of carbon in saline soil was 30% and 39% after addition of wheat and mungbean residues, respectively (Khalil *et al.*, 2005). This indicates that saline soil affects C mineralization to various degrees after addition of different organic residues and salts. This also changes soil pH (Rukshana *et al.*, 2012, 2013) in different ways, directions, and magnitudes depending on initial soil pH, chemical composition of organic residue and microbial activities especially CO₂ emission (Khalil *et al.*, 2001). The rate of C mineralization in the saline soils may decrease or increase according to change in soil pH and, thereby, change the other soil properties (Khalil *et al.*, 2005). It appears that organic matter with high C:N might result in a reduced C loss because of slow decomposition rate under aerobic saline conditions; this further depends on the quality and quantity of C source in the soil and extent of C released (Khalil *et al.*, 2001). For instance, CO₂ was higher with 5 g C kg⁻¹ soil than with 2.5 g C kg⁻¹ soil (quantity), and glucose treatment enhanced respiration over the cellulose treatment (quality). The microbes in saline conditions decompose cellulose more easily than glucose (Elmajdoub & Marschner, 2013). The effect of salinity on potential of microbes to mineralize C from various sources and states is also not well known. In this context, the response of SMB and activity was determined in an incubation experiment to salinity when supplied with two different carbon forms (glucose and cellulose) (Elmajdoub & Marschner, 2013). Yan & Marschner (2012) reported that microbes isolated from saline soils showed less tolerance to increasing salinity than those isolated from non-saline soils. It is assumed that addition of residue may increase MB because of a small set of microbes in all soils feed on added residues in saline soils (Yan & Marschner, 2012). They further extended their work (Yan & Marschner, 2013) and established an experiment with a range of saline levels created artificially in which pea straw was added as a nutrient source. At artificially created salinity levels, respiration recorded similar to that of soils that had originally lower salinity. This suggests that structure and function of soil microbial community can rapidly increase when the substrate is added and salinity decreased.

Despite the fact that salinity changes with water content in soil, little is known about effects of moisture content on SR and microbial activities. Fluctuations in water content (water potential) tremendously affect SMAs (Setia & Marschner, 2013a; Yan & Marschner, 2013). In soils with high concentration of salts may show more pronounced effects. Wetting of dry soils always induce gaseous emissions including CO₂, which may decrease with increase in time. This trend in saline soils is thought to be due to dispersion of clay minerals, exposure of organic substrates, release of osmolytes due to cell lysis, and breakdown of aggregates (macro to micro) (Chowdhury *et al.*, 2011b). Several other factors may also affect the SMAs like interval between rewetting and drying, initial osmotic potential, soil fertility, structure, addition of substrate, and irrigation levels. An increase in drying–rewetting cycles lowers flush of CO₂ (Chowdhury *et al.*,

2011b). The magnitude of alteration in aggregates because of introducing water in soil affects microbial activities. The sudden wetting of soil destroys aggregates and exposes organic matter for microbial assimilation, but at later stages, wetting does not affect aggregation to the similar scale (Chowdhury *et al.*, 2011a).

Setia & Marschner (2013b) studied the effect of osmotic, matric, and water potential, and substrate composition on microbial activity and biomass in saline soils amended with wheat and pea residues. In this study, cumulative respiration decreased with decreasing water potential, and the relative decrease in microbial activity suggests that the small biomass in saline soils does not tolerate low osmotic potential (Setia & Marschner, 2013a). Hence, drying of soil would have negative effect on microbial activity in saline than in non-saline soils (Setia & Marschner, 2013b). Similarly, Mavi & Marschner (2012) studied the impact of multiple drying and wetting on microbial respiration, dissolved organic carbon, and microbial biomass in salt-affected soils. Rewetting of dry soils resumed respiration in the slightly saline soils but could not in moderately saline soils, which suggest the better substrate utilization by microbes in less saline soils. Iwai *et al.* (2012) investigated the effect of alternative wet-dry tropical climatic conditions. They found an increase in exchangeable Na⁺ during dry season that indicates upward movement of salts on the soil surface during the dry season. The significant negative exponential relationships between EC and microbial activities were observed during dry and wet seasons.

CO₂ Emission or C Mineralization in Sodic Soils

Sodic soils are characterized with a very low SOM because of less C sequestration and high decomposition rates. Sodicity may influence the decomposition of SOM both directly and indirectly to have a relatively low SOM in the soil. Sodicity influence the structure (shape, size, and arrangements of particles and pores in soil) and, thereby, minerals' behavior (slaking, swelling, and dispersion), which plays an important role in microbial and faunal activities and trophic interactions (Nelson & Oades, 1998). A high level of sodium (Na) makes SOM more accessible for microbial decomposition by dissolving and dispersing. The positive effect of Na⁺ on decomposition could be greatest for small anionic substrates and least for particulate uncharged substrates. The anaerobic condition caused by sodicity may decrease mineralization in the field through their negative effect on microbial activities. As the level of sodicity determines the quality and quantity of SOM, the reciprocal effects of SOM on soil sodicity are also noticed in different ways. The cation exchange capacity and the selectivity of exchange sites for Ca over Na, and ability of SOM to donate protons have significant effects on sodicity. In conclusion, sodicity may increase the mineralization of SOM by making it more accessible for microbial decomposition, but at the same time, it may also decrease mineralization in submerged conditions because of the effects of anaerobic condition on microbial community (Wu *et al.*, 2013).

Amending sodic soils with Ca salts decreased C mineralization (less CO₂ emission) under both laboratory and field

conditions (Muneer & Oades, 1989a, 1989b) because Na^+ is more effective in prevailing dispersion of clay minerals than Ca^{++} (Sumner, 1993). Decrease in SR might also be due to decreased dispersion of SOM and clay particles by amending soils with Ca^{++} . However, addition of organic matter facilitates the dissolution of CaCO_3 ; in that case, CO_2 evolution is increased. The evolved CO_2 may also be trapped in the soil solution through formation of $\text{Ca}(\text{HCO}_3)_2$ (Oren & Steinberger, 2008; Macci *et al.*, 2013). There is a need to relate the CO_2 evolution with total (insoluble) and active (soluble) CaCO_3 in the soil with different salinity and sodicity levels.

N Mineralization in Salinity and Sodidity

The mineralization of N in salt-affected soils is a subject of deep insight because of preliminary controversial studies (Laura, 1974, 1975, 1976; Nelson *et al.*, 1996; Pathak & Rao, 1998). Salinity and sodicity of soil have its effects on C and N mineralization, which are crucial for plant growth and soil fertility. Ammonification is stimulated at low salt concentration and inhibited at higher amounts of salts, but nitrification is very sensitive because ammonifiers are more tolerant than nitrifiers (Westerman & Tucker, 1974; McCormick & Wolf, 1980; McClung & Frankenberger, 1987; Pathak & Rao, 1998). Laura (1974) reported that ammonification is continued to increase with increasing salinity. However, the ammonification apparently increased up to $\text{EC } 70 \text{ dS m}^{-1}$, while nitrification was stimulated only up to $\text{EC } 16 \text{ dS m}^{-1}$ and completely inhibited at $\text{EC } 26 \text{ dS m}^{-1}$ (Pathak & Rao, 1998). Therefore, salinity causes a significant decrease in N mineralization. Stimulation of ammonification at low salinity may be explained on the basis of solubilization of SOM and osmotic effects on microbes (Broadbent & Nakashima, 1971) releasing carbonaceous substrates (Pathak & Rao, 1998). Increased solubilization of SOM at high pH may lead to increase N mineralization. In sodic soils, $\text{NH}_4\text{-N}$ was not detected, and there was significant increase in $\text{NO}_3\text{-N}$ with increasing soil pH and ESP (Pathak & Rao, 1998). This reveals that increasing sodicity stimulated N mineralization but the values of net N mineralization, as a fraction of organic N, showed a small decrease with increase in soil pH (Pathak & Rao, 1998). For instance, increase in $\text{NO}_3\text{-N}$ concentration with increase in pH or ESP is not real stimulation of nitrification. Rietz & Haynes (2003) presented negative relationship of N mineralization and ammonification with EC, SAR, and ESP. This indicates that increase in salinity and sodicity is harmful to the most of the microbes, and in that case, less metabolically efficient soil microbes mediate soil processes including C, N, P, and S mineralization. The decomposition of SOM is generally reduced with effect of salinity, but it may be unaffected or increased with effect of sodicity (Nelson *et al.*, 1996). In any case, if the decomposition rate is decreased by salinity or sodicity; it is directly associated with the inhibitory microbial growth and activity (Rietz & Haynes, 2003).

The concentration of $\text{NO}_3\text{-N}$ increased (stimulation of nitrification) in sludge amended soil with high salt content and pH 10.2 (Dendooven *et al.*, 2010), while high salt contents and pH are known to inhibit oxidation of NH_4^+ and NO_2^- (Oren, 1999, 2002). The amount of NH_4^+ and easily decomposable organic material available in soil amendment also affect the rate of nitrification and ammonification in saline and sodic soils (Dendooven *et al.*, 2010). The decrease in $\text{NH}_4\text{-N}$ might be due to NH_3 volatilization at high pH (Sommer & Ersbøll, 1996) and adsorption of NH_4^+ on soil particles (Drury *et al.*, 1991). In other cases, an increase in $\text{NH}_4\text{-N}$ with increasing salinity and sodicity appears that microbes in these soils immobilized $\text{NH}_4^+\text{-N}$ in excess of what was necessary for metabolic activity (Dendooven *et al.*, 2010).

Soil Microbial Biomass, Population, and Quotients with Salinity and Sodidity

It is clear from previous sections that, when microbial population is under stress, more C is lost through respiration rather than being converted to their own growth and humus formation. In most of cases, the mineralized N is decreased with increasing salinity and sodicity levels in soil. It would be interesting to know how microbial biomass, population, and potential enzyme activities are responding to salinity and sodicity stress. The quality and quantity of organic residue (substrates) and soil environment play important roles in microbial assimilation of soil organic carbon. Low SOM and high salinity may establish an undesirable environment for the development of bacterial and fungal community, and in contrast, high organic matter and low salinity may favor the fungal growth (Yuan *et al.*, 2007). Muhammad *et al.* (2006) found a higher fraction of fungal biomass in the more saline soil compared with less saline soils. Besides, in tropical and subtropical climate where saline and sodic soils are found, decomposition process is largely carried out by bacteria; whereas in temperate climate, fungi may perform major role in this process.

Salinity and sodicity exert detrimental effects on both microbial biomass and thereby on metabolic quotient. Therefore, the metabolic quotient may indicate the response of microbial population under stress (salinization and sodication) (Wong *et al.*, 2008, 2005). Chander *et al.* (1994) reported that MBC reduced to one-third in the soils treated with 16 me l^{-1} residual sodium carbonate (RSC) irrigation water in comparison with that of treated with 2.8 me l^{-1} RSC irrigation water. This study indicates that an increase in sodicity over a critical level affects microbial biomass identically. Yuan *et al.* (2007) reported significant negative exponential relationship between EC (salinity) and microbial biomass C and N and microbial quotients. The highest values of $q\text{CO}_2$ in the most of the saline and sodic soils indicate low substrate availability and poor functioning of microorganisms (Anderson & Domsch, 1990; Wong *et al.*, 2009) and variations in the composition of the microbial communities (Tripathi *et al.*, 2006). The low percentage of MBC to that of SOC demonstrates that salinity

is detrimental to microorganisms (Yuan *et al.*, 2007); however, it is also noticed that considerable microbial activity persisted in saline soils because of accumulation of osmolytes in salt tolerant bacteria (Tejada *et al.*, 2006; Yuan *et al.*, 2007; Chowdhury *et al.*, 2011c; Asghar *et al.*, 2012). Chowdhury *et al.* (2011) and Setia *et al.* (2011a, 2011b) reported the decrease in SR with increasing salinity even after addition of substrate. It was speculated that higher metabolic quotient and low MBC at high soil salinity might be due to either a shift in microbial community with less catabolic activity or reduced efficiency to utilize substrate.

With the increasing level of salinity a consistent decrease in SR was reported, while MBC was unaffected (Ghollarata & Raiesi, 2007). Wong *et al.* (2008) also observed highest SR in low level of soil salinity and lowest in high level of soil salinity, while SMB was highest in the high-salinity soils and lowest in low-salinity soils. They postulated that highest microbial biomass in high-salinity soils was due to more substrate availability, high salt concentrations, high dispersion of aggregates, and high solubility of organic matter. Thus, reduced efficiency of substrate utilization by the soil microflora could be a mechanism by which salinity depresses microbial respiration even with added organic matter. Singh *et al.* (2012a), in their field study, reported lowest microbial biomass and SR (CO₂ efflux) in sodic soils with 95% (ESP); values of SMB and SR increased with decreasing sodicity when the soil was reclaimed substantially by afforestation and cropping over the years.

Osmotic desiccation in saline environment may lead to microbial cell lysis of less tolerant microbes (Dinesh *et al.*, 1995). Salinity and low nitrogen content may limit microbial activity and residue decomposition rate (Elgharably & Marschner, 2011). Elgharably & Marschner (2011) studied the effects of NH₄-N or NO₃-N and addition of lupin residues on microbial biomass and activity in a saline sandy loam. Soil microbial biomass (SMB) decreased with increasing salinity but significantly increased with residue addition. The greater C availability in the lupin residue amended saline sandy loam soil and stimulated microbial activity and

biomass with greater N demand, thus promoted immobilization of NO₃. Rietz & Haynes (2003), in agreement with Galinski (1995) and Oren (1999), also proved that, in saline soils, osmotic stress limits the microbial growth and activity and causes dehydration of microorganisms. In sodic environment, however, Na toxicities and high pH may inhibit microbial growth (Rietz & Haynes, 2003). Increase in SMB and SR was observed with addition of two organic wastes (cotton gin crushed compost, CGCC, and poultry manure, PM) to saline soils by Tejada *et al.* (2006). However, SMB and SR were higher in PM than in CGCC-amended soils, while decrease in ESP was higher in CGCC-amended soils. It was postulated that this might be because of greater labile carbon, N, and P content in PM than in CGCC. This might also be attributed to (i) microbial growth and enzyme activities exist in these organic wastes, (ii) higher sodicity (ESP) and substrate availability in PM than CGCC-amended soils, and (iii) dispersion of soil aggregates (Wong *et al.*, 2008).

I have derived a generalized pattern of CO₂ emission, N-mineralization, microbial biomass, and enzyme activities (Figure 2) through reviewing the data from the literature cited in preceding sections. It is observed that microbial activities may differ in response to substrate in a particular soil condition; when we add the substrate, it may show entirely different response. In the absence of adequate organic matter (organic substrate), CO₂ emission increases with increasing salinity and sodicity, while N-mineralization, microbial biomass, and enzyme activities decreased (Figure 2a). On the other hand, the case may be vice versa when an organic substrate (ranging from organic molecules to crop residues or organic matter) is added externally to salt-affected soils CO₂ emission increases with respect to increasing salinity and sodicity and N-mineralization, microbial biomass and enzyme activities increase to attain an equilibrium (steady state). Therefore, it is clear that response of microbial activities to soil salinization and sodication depends on quality and quantity of inherent organic substrates as well as externally added to salt-affected soils.

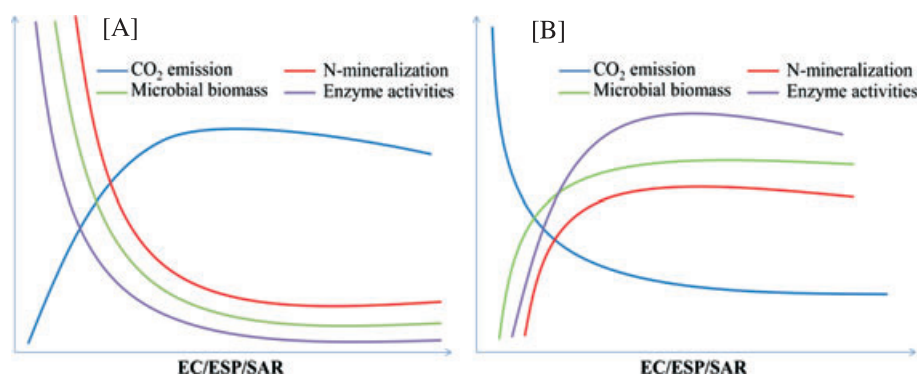


Figure 2. The effect of salinity (EC) and sodicity (ESP or SAR) on microbial activities [A] without substrate addition and [B] after substrate addition. EC, electrical conductivity; ESP, exchangeable sodium percentage. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Microbial Community Structure and Function with Salinity and Sodicity

Identification of microorganisms through the traditional culture dependent techniques remains limited to less than 1% of the bacterial diversity. However, several physiological (community level physiological profiling), biochemical (phospholipid fatty acid analysis; PLFA) (Singh *et al.*, 2004), and molecular (microbial DNA fingerprinting) methods (Dubey *et al.*, 2006) (culture-independent techniques) are in use to investigate the soil microbial diversity (Singh *et al.*, 2004). Rousk *et al.* (2011) studied the influence of soil salinity on soil bacterial communities in a range of salt levels. The clear concentration response relationship was established between bacterial growth and soil salinity, demonstrating an accurate assessment of bacterial tolerance. They reported that soil salinity was not a decisive factor for bacterial growth and thus for structuring the decomposer community in the studied soils. Similarly, Asghar *et al.* (2012) reported that microbial community composition (based on PLFA) and activities of microorganisms isolated from saline and non-saline soils respond similarly to changes in salinity. This might be because of modified physiological and structural characteristics of the microbial communities in saline environment (Zahran, 1997; Ventosa *et al.*, 1998; Rietz & Haynes, 2003; Rao & Pathak, 1996). However, these findings did not consider other factors existing in natural field soils.

Wu *et al.* (2012) ameliorated seashore saline soil by planting castor bean (*Ricinus communis* L.) for two growing seasons. After 2 years of growth, soil salinity was 0.92% lower than that unplanted soil; the activity and biodiversity of soil microbial communities (based on community level physiological profiling) and functional and metabolic diversity of halophilic, phosphate-solubilizing, potassium-solubilizing, cellulose decomposing, ammonifying, and nitrogen-fixing bacteria increased markedly in the planted plots in comparison with control plots. The increase in functional microorganism that can fix atmospheric nitrogen, solubilize phosphate, potassium, or decompose plant residues can improve soil structure and enhance soil nutrient availability (Wu *et al.*, 2012). In China, flue gas desulfurization gypsum by-product (FGDB) has been recognized as a new ameliorant for saline and sodic soils (Wang *et al.*, 2012; Li *et al.*, 2012). The responses of soil microbial communities to FGDB were examined using PLFA and real time quantitative polymerase chain reaction. Microbial community composition differed along the FGDB gradient; however, the microbial parameters did not follow a linear response. They found total PLFA concentrations, and concentrations of total bacterial and gram-negative bacteria PLFAs were slightly higher at intermediate FGDB concentrations. Similar results were obtained for the 16S rRNA copy numbers of bacteria at 0–20 cm depth. Shifts in PLFA-based microbial community composition and biomass could partly be explained by changes in soil physicochemical properties. Results conclude that addition of FGDB leads to significant changes in soil physicochemical and microbial parameters

(Li *et al.*, 2012). Molecular phylogeny revealed the dominance of *Actinobacteria*, *Firmicutes* and *Proteobacteria* along with archaeal members of *Halobacteraceae* in saline-sodic soils (Keshri *et al.*, 2013). The library consisted of novel bacterial (20%) and archaeal (38%) genera showing $\leq 95\%$ similarity to previously retrieved sequences. Phylogenetic analysis indicated the ability of inhabitant to survive in saline and sodic conditions.

Microbial Enzymes in Saline and Sodic Soil

Soil enzymes are, generally, considered very sensitive to changes in soils and have been proposed as indicators to measure degree of soil stresses (Schmidt *et al.*, 2011; Nannipieri *et al.*, 2012). In spite of the extensive bibliography on the effects of soil use and management on potential soil enzyme activity, a very few studies have been focused on the effects of salinization and sodication on the enzyme activities. It is therefore of great interest to investigate how soil enzymes are affected by salinity and sodicity and which processes are responsible for their altered activities. Soil salinity and sodicity affect the activity of soil enzymes through its direct influence on microbial enzymatic production and structural changes in enzymes due to anionic movement and availability of organic matter (Frankenberger & Bingham, 1982; Amato & Ladd, 1992; Yao *et al.*, 2009).

An increase in soil salinity or sodicity inhibits the activity of dehydrogenase, β -glucosidase, urease, protease, alkaline phosphatase, acidic phosphatase, arylsulphatase, and argininamide hydrolyzing activity (Frankenberger & Bingham, 1982; Chander *et al.*, 1994; Garcia & Hernandez, 1996; Rietz & Haynes, 2003; Tejada *et al.*, 2006; Tripathi *et al.*, 2007). Pathak & Rao (1998) reported that sodicity does not affect glutaminase and deaminase activities, while the activities of asparaginase and deaminase were not resistant to salinity and sodicity, respectively. This might be attributed to enzyme specific activity with respect to salinity and sodicity. Rietz & Haynes (2003) also reported the activities of β -glucosidase, alkaline phosphatase, and arylsulphatase decreased with increasing salinity (EC) and sodicity (ESP). The activity of arylsulphatase was less affected by salinity (EC) and sodicity (ESP). Inhibited activity of soil enzymes in saline soils appears to be associated with the physicochemical and microbial properties of soils (Frankenberger & Bingham, 1982). The decline in enzyme activity with increasing salinity also appeared to be related to change in osmotic potential of the soil because of higher salt concentrations and specific ion toxicity (Zahir *et al.*, 2001). The NaCl (salt stress) induced changes in enzyme activities; this negative effect was even greater on hydrolases (phosphatase and β -glucosidase).

The activities of alkaline phosphatase and acidic phosphatase were higher in sodic (alkaline in old literature) and acidic soils, respectively (Tripathi *et al.*, 2007; Dick *et al.*, 2000; Singh *et al.*, 2012a, 2012b). Generally, alkaline phosphatase predominated in soils with neutral or slightly alkaline pH. It has been observed that activity of soil enzymes depends on microbial growth and availability of resources

and nutrients (Sinsabaugh & Moorhead, 1994). The activity of alkaline phosphatase might be dependent on availability of labile phosphorus in the soils (Singh *et al.*, 2012a). The amount of inorganic P increased with increasing alkalinity and soil pH in sodic soils of semi-arid region. When soil microorganisms are phosphorus (P) limited, they produce acid or alkaline phosphatase (depending upon soil pH and microbial community composition) that release inorganic phosphate from organic matter (Allison *et al.*, 2011). Moreover, phosphatase activity has been shown to be inversely related to inorganic P availability in the soil system, especially in salt-affected soils (Allison *et al.*, 2007; Allison *et al.*,

2011). This relationship also holds at the global scale, where the ratio of P and carbon acquiring extracellular enzymes increases in tropical ecosystems; where P is more likely to limit productivity because of increased P weathering rates (Sinsabaugh *et al.*, 2008). Rao *et al.* (2000) reported that acid phosphatase–montmorillonite and acid phosphatase–tannate complexes had different pH-activity dependence and a higher and lower sensitivity to temperature and proteolysis, respectively. They concluded that phosphatase immobilized on clays, organic, and organo-mineral complexes showed catalytic features quite different from those of the free enzyme.

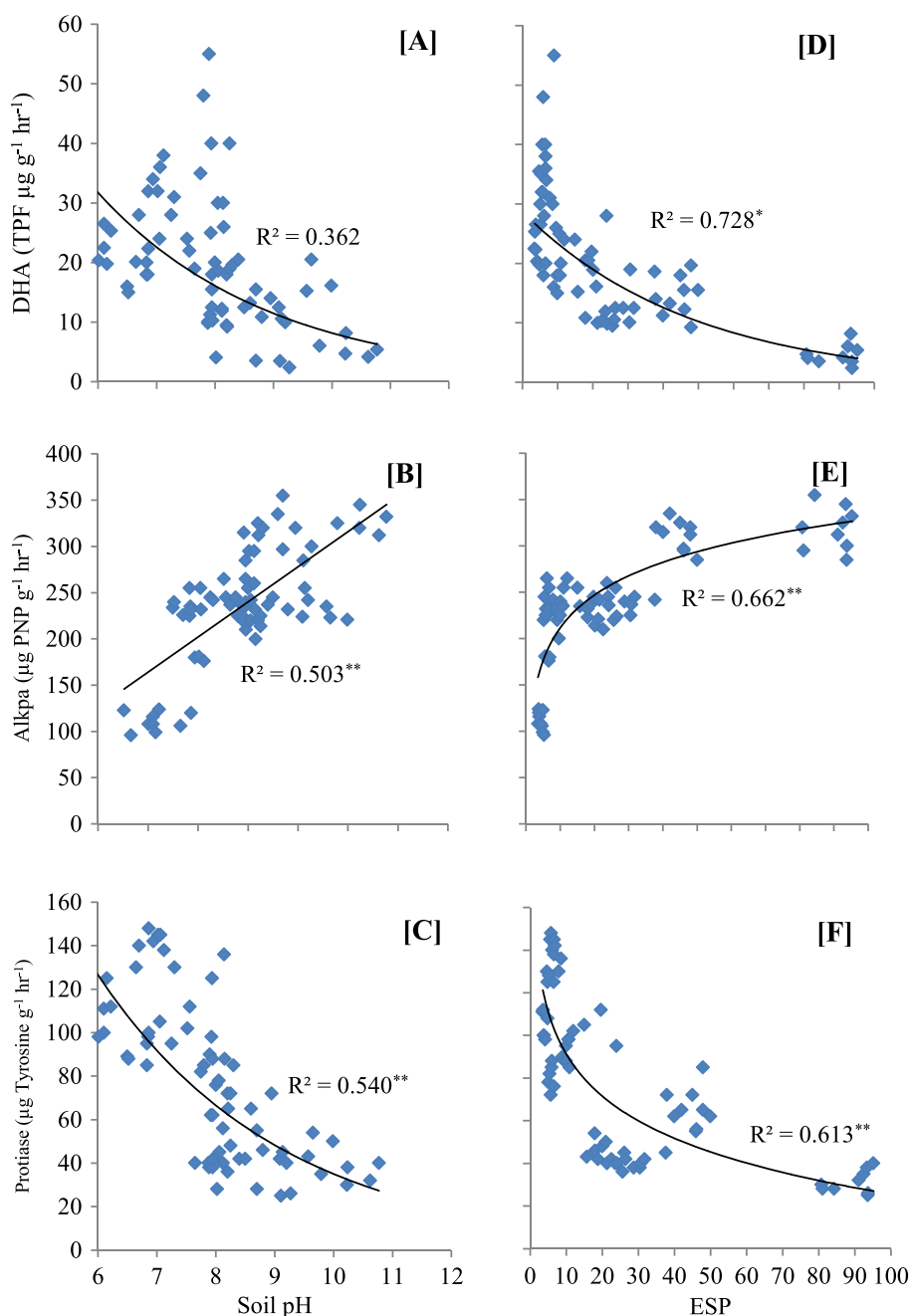


Figure 3. Relationship of dehydrogenase (DHA), alkaline phosphatase (Alkpa) and protease with soil pH [A, B, C] and exchangeable sodium percentage (ESP) [D, E, F] in a range of sodic soils. (*) P, 0.05; (**) P, 0.01. ESP, exchangeable sodium percentage. This figure is available in colour online at wileyonlinelibrary.com/journal/ldr

Garcia *et al.* (1994) reported that reduction in enzyme activities may be attributed to lower microbial growth and biomass; thereby, less release in soil enzymes. In semi-arid soils, the enzyme activity is mainly extracellular, stable, and form complexes with the organic and mineral colloids (Schmidt *et al.*, 2011; Nannipieri *et al.*, 2012). Salt-tolerant microbes in salt-affected soils produce enzymes, which have optimum activities under higher salt concentration than corresponding enzymes produced by microbes in non-saline soils (Zahran, 1997). There are inverse relationships of soil pH and ESP with enzyme activities that generally show non-linear model (logarithmic, exponential, or polynomial) in a range of sodic soils. It was observed that protease enzyme decreased significantly with increasing soil pH, except alkaline phosphatase. While the dehydrogenase and protease showed a statistically significant negative relationship with ESP, alkaline phosphatase had significant positive relationship with ESP. The relationship of dehydrogenase with soil pH was weak (Figure 3). Soil pH has direct biochemical effects on activity of extracellular soil enzymes (Sinsabaugh *et al.*, 2008). Soil pH reflects climatic controls on soil weathering and affects the large-scale distribution of soil enzymes through changes in nutrient availability (Sinsabaugh *et al.*, 2008). The increase in EC disperses the clays, and the stable enzymes remain unprotected and therefore become more prone to denaturation (Frankenberger & Bingham, 1982; Pathak & Rao, 1998).

Garcia & Hernandez (1996) reported that NaCl was more effective than Na₂SO₄ in negatively affecting biological and biochemical fertility of soils, attributed to the toxic effect of particular ion on microbial growth in saline soils. Probably, chloride toxicity is greater than sulfate (Frankenberger & Bingham, 1982; Zahran, 1997; Pathak & Rao, 1998; Rietz & Haynes, 2003; Tejada *et al.*, 2006). The addition of organic wastes had a positive effect on the activities of soil enzymes (Tejada *et al.*, 2006). Lower values of enzyme activities in saline soils than in non-saline soils might be due to following two reasons: (i) 'salting-out' effect, which involves a decrease in enzyme solubility through dehydration, thus altering the enzyme 'catalytic site'; and (ii) enzymes in saline soils are less protected and perhaps they were denatured by proteolysis (Garcia *et al.*, 2000). Recently, Pan *et al.* (2013) investigated that not all enzymes are sensitive to salinity. Urease was proved to have serious limitation with respect to its ability to reflect grassland salinization. Both β -glucosidase and alkaline phosphatase may be used as indicators of soil quality during grasslands salinization. Kang *et al.* (2013) assessed the changes and spatial distributions of soil enzyme activities in saline-sodic soil for 3 years of cultivation of *Leymus chinensis* under drip irrigation. Alkaline phosphatase, urease, and sucrase activities increased with cultivated years in saline-sodic soil under drip irrigation after planting *L. chinensis* for 3 years.

The available contradictory findings give generous justification for further investigations into the effects of salinity on C–N dynamics and structure, function, and diversity of soil microbial communities. I suggest following key research

issues to be addressed in future. What is the pattern of C–N dynamics in saline and sodic soils in relation to seasonal variations? How do salinity and sodicity affect N cycling, and will N dynamics follow the pattern similar to that of C dynamics? How is changing sodicity (in field conditions) likely to impact enzyme–mineral interactions, and will there be its any effect on C–N dynamics? Can we link diversity of mycorrhizal fungi and bacteria with aggregate stability in sodic soils? How we can manipulate these microbes to minimize C loss (CO₂ emission) and maximize C stocks in saline and sodic soils? Are there distinct microbial (bacteria and fungus) species in relation to C–N dynamics at various salinity and sodicity levels in field soils? How dissolution of CaCO₃ (available in plenty in sodic soils) affects decomposition of organic matter, C–N mineralization, and microbial activities in sodic soils? How drying and rewetting of sodic soils from field, not in artificially created saline and sodic soils, affect C–N dynamics and microbial activities? What is the pattern of change in structure, function, and diversity of microbial communities during salinization and sodication? These issues are mysterious and need further investigations.

CONCLUSIONS

It is concluded that excess amounts of salts in soil not only have adverse effects on soil physical and chemical properties but also affect the microbial and enzyme activities. Both soil salinity and sodicity have detrimental effects on microbial communities (structure, function, and diversity). Drying and rewetting affect microbial activities of saline soils. The magnitude of its effect depends on salt concentration and availability of organic substrates in the soil. Because of structural instability, sodic soils are more prone to loss of soil organic carbon through C mineralization (CO₂ emission). An increase in sodicity level tends to increase dispersion of clay particles, and this makes organic matter more accessible for microbial action. The microbial biomass, population, and values of potential soil enzyme activities are generally decreased with increasing salinity and sodicity of soil, which restrict the efficient N cycling.

ACKNOWLEDGEMENTS

Author expresses his sincere thanks to Council of Scientific and Industrial Research, New Delhi, India for awarding CSIR-Nehru Science Postdoctoral Research Fellowship (HRDG/CSIR-Nehru PDF/LS/EMR-I/03/2013). This review was substantially improved after my discussion with Bajrang Singh, D.D. Patra, and Rana P. Singh. I am thankful to Prof. Artemi Cerda for his support throughout the production of this review. Two anonymous reviewers' comments also helped me a lot to improve this review.

REFERENCES

- Abiven S, Menasseri S, Chenu C. 2009. The effects of organic inputs over time on soil aggregate stability – a literature analysis. *Soil Biology & Biochemistry* **41**: 1–12.

- Abrol IP, Bhumbla DR. 1971. Saline and alkali soils in India – their occurrence and management. *World Soil Resources*, FAO Report **41**: 42–51.
- Agarwal AS, Singh BR, Kanehiro Y. 1971. Ionic effect of salts on mineral nitrogen release in an allophanic soil. *Soil Science Society American Journal* **35**: 454–457.
- Allison VJ, Condron LM, Peltzer DA, Richardson SJ, Turner BL. 2007. Changes in enzyme activities and soil microbial community composition along carbon and nutrient gradients at the Franz Josef chronosequence, New Zealand. *Soil Biology & Biochemistry* **39**: 1770–1781.
- Allison SD, Weintraub MN, Gartner TB, Waldrop MP. 2011. Evolutionary-economic principles as regulators of soil enzyme production and ecosystem function. In *Soil Enzymology*, Shukla G, Varma A (eds). Springer: Berlin, Germany; 229–243.
- Amato M, Ladd JN. 1992. Decomposition of ¹⁴C-labeled glucose and legume material in soils: properties influencing the accumulation of organic residue C and microbial biomass C. *Soil Biology & Biochemistry* **24**: 455–464.
- Anderson T-H, Domsch KH. 2010. Soil microbial biomass: the eco-physiological approach. *Soil Biology and Biochemistry* **42**: 2039–2043.
- Anderson TH, Domsch AK. 1993. The metabolic quotient for CO₂ qCO₂ as a specific activity parameter to assess the effects of environmental conditions, such as pH, on the microbial biomass of forest soils. *Soil Biology & Biochemistry* **25**: 393–395.
- Anderson T-H, Domsch KH. 1990. Application of eco-physiological quotients (qCO₂ and qD) on microbial biomasses from soils of different cropping histories. *Soil Biology and Biochemistry* **22**: 251–255.
- Asghar HN, Setia R, Marschner P. 2012. Community composition and activity of microbes from saline soils and non-saline soils respond similarly to changes in salinity. *Soil Biology & Biochemistry* **47**: 175–178.
- Balota EL, Yada IF, Amaral H, Nakatani AS, Dick RP, Coyne MS. 2013. Long-term land use influences soil microbial biomass P and S, phosphatase and arylsulfatase activities, and S mineralization in a Brazilian Oxisol. *Land Degradation & Development*. DOI: 10.1002/ldr.2242.
- Beltrán-Hernández RI, Luna-Guido ML, Dendooven L. 2007. Emission of carbon dioxide and dynamics of inorganic N in a gradient of alkaline saline soils of the former lake Texcoco. *Applied Soil Ecology* **35**: 390–403.
- Broadbent FE, Nakashima T. 1971. Effect of added salts on nitrogen mineralization in three California soils. *Soil Science Society of America Proceedings* **35**: 457–460.
- Campos AC, Etchevers JB, Oleschko KL, Hidalgo CM. 2013. Soil microbial biomass and nitrogen mineralization rates along an altitudinal gradient on the Cofre de Perote Volcano (Mexico): the importance of landscape position and land use. *Land Degradation & Development*. DOI: 10.1002/ldr.2185.
- Chander K, Goyal S, Kapoor KK. 1994. Effect of sodic water irrigation and farmyard manure application on soil microbial biomass and microbial activity. *Applied Soil Ecology* **1**: 139–144.
- Chowdhury N, Marschner P, Burns RG. 2011a. Soil microbial activity and community composition: impact of changes in matric and osmotic potential. *Soil Biology & Biochemistry* **43**: 1229–1236.
- Chowdhury N, Marschner P, Burns R. 2011b. Response of microbial activity and community structure to decreasing soil osmotic and matric potential. *Plant and Soil* **344**: 241–254.
- Chowdhury N, Marschner P, Burns RG. 2011c. Soil microbial activity and community composition: impact of changes in matric and osmotic potential. *Soil Biology and Biochemistry* **43**: 1229–1236.
- Coleman DC, Reid CPP, Cole CV. 1985. Biological strategies of nutrient cycling in soil system. *Advances in Ecological Research* **13**: 1–57.
- Davidson EA, Janssens IA, Luo Y. 2006. On the variability of respiration in terrestrial ecosystems: moving beyond. *Global Change Biology* **12**: 154–164.
- Dendooven L, Alcántara-Hernández RJ, Valenzuela-Encinas C, Luna-Guido M, Perez-Guevara F, Marsch R. 2010. Dynamics of carbon and nitrogen in an extreme alkaline saline soil: a review. *Soil Biology & Biochemistry* **42**: 865–877.
- Dick WA, Cheng L, Wang P. 2000. Soil acid and alkaline phosphatase activity as pH adjustment indicators. *Soil Biology & Biochemistry* **32**: 1915–1919.
- Dinesh R, Ramanathan G, Singh H. 1995. Influence of chloride and sulphate ions on soil enzymes. *Journal of Agronomy and Crop Science* **175**: 129–133.
- Drury CF, Voroney RP, Beauchamp EG. 1991. Availability of NH₄-N to microorganisms and the soil internal N cycle. *Soil Biology & Biochemistry* **23**: 165–169.
- Dubey SK, Tripathi AK, Upadhyay SN. 2006. Exploration of soil bacterial communities for their potential as bioresource. *Bioresource Technology* **97**: 2217–2224.
- Egamberdieva D, Renella G, Wirth S, Islam R. 2009. Secondary salinity effects on soil microbial biomass and activity. *Biology and Fertility of Soils* **46**: 445–449.
- Elgharably A, Marschner P. 2011. Microbial activity and biomass and N and P availability in a saline sandy loam amended with inorganic N and lupin residues. *European Journal of Soil Biology* **47**: 310–315.
- Elliott ET. 1986. Aggregate structure and carbon, nitrogen, and phosphorus in native and cultivated soils. *Soil Science Society of America Journal* **50**: 627–633.
- Elmajdoub B, Marschner P. 2013. Salinity reduces the ability of soil microbes to utilise cellulose. *Biology and Fertility of Soils* **49**: 339–346.
- Ferreira ACC, Leite LFC, Araújo ASF, Eisenhauer N. 2015. Land-use type effects on soil organic carbon and microbial properties in a semi-arid region of northeast Brazil. *Land Degradation & Development*. DOI: 10.1002/ldr.2282.
- Frankenberger WT, Bingham FT. 1982. Influence of salinity on soil enzyme activities. *Soil Science Society American Journal* **46**: 1173–1177.
- Fterich A, Mahdhi M, Mars M. 2014. The effects of *Acacia tortilis* subsp. *raddiana*, soil texture and soil depth on soil microbial and biochemical characteristics in arid zones of Tunisia. *Land Degradation & Development* **25**: 143–152. DOI: 10.1002/ldr.1154.
- Galinski EA. 1995. Osmoadaptation in bacteria. *Advances in Microbial Physiology* **37**: 273–328.
- García C, Hernandez T. 1996. Influence of salinity on the biological and biochemical activity of a calciorthid soil. *Plant and Soil* **178**: 255–263.
- García C, Hernandez T, Costa F. 1994. Microbial activity in soils under Mediterranean environmental conditions. *Soil Biology and Biochemistry* **26**: 1185–1191.
- García C, Hernandez T, Pascual JA, Moreno JL, Ros M. 2000. Microbial activity in soils of SE Spain exposed to degradation and desertification processes. Strategies for their rehabilitation. In *Research and perspectives of soil enzymology in Spain*, Garcia C, Hernandez MT (eds). CEBAS-CSIC: Spain; 93–143.
- García-Orenes F, Guerrero C, Roldán A, Mataix-Solera J, Cerdà A, Campoy M, Zornoza R, Bárcenas G, Caravaca F. 2010. Soil microbial biomass and activity under different agricultural management systems in a semiarid Mediterranean agroecosystem. *Soil & Tillage Research* **109**: 110–115.
- Ghollarata M, Raiesi R. 2007. The adverse effects of soil salinization on the growth of *Trifolium alexandrinum* L. and associated microbial and biochemical properties in a soil from Iran. *Soil Biology & Biochemistry* **39**: 1699–1702.
- Gianfreda L, Rao MA. 2011. The influence of pesticides on soil enzymes. In *Soil Enzymology*, pp. 293–312. Springer: Berlin Heidelberg.
- Gill JS, Sale PWG, Peries RR, Tang C. 2008. Amelioration of dense sodic subsoil using organic amendments increases wheat yield more than using gypsum in a high rainfall zone of southern Australia. *Field Crops Research* **107**: 265–275.
- Gill JS, Sale PWG, Peries RR, Tang C. 2009. Changes in soil physical properties and crop root growth in dense sodic subsoil following incorporation of organic amendments. *Field Crops Research* **114**: 137–146.
- Guénon R, Vennetier M, Dupuy N, Roussos S, Pailler A, Gros R. 2013. Trends in recovery of Mediterranean soil chemical properties and microbial activities after infrequent and frequent wildfires. *Land Degradation & Development* **24**: 115–128. DOI: 10.1002/ldr.1109.
- Hagemann M. 2011. Molecular biology of cyanobacterial salt acclimation. *FEMS Microbial Reviews* **35**: 87–123.
- Iwai CB, Oo AN, Topark-Ngarm B. 2012. Soil property and microbial activity in natural salt affected soils in an alternating wet–dry tropical climate. *Geoderma* **189–190**: 144–152.
- Kang YH, Liu SH, Wan SQ, Wang RS. 2013. Assessment of soil enzyme activities of saline–sodic soil under drip irrigation in the Songnen plain. *Paddy and Water Environment* **11**: 87–95.
- Keshri J, Mishra A, Jha B. 2013. Microbial population index and community structure in saline-alkaline soil using gene targeted metagenomics. *Microbiological Research* **168**: 165–173.
- Khalil MI, Hossain MB, Schmidhalter U. 2005. Carbon and nitrogen mineralization in different upland soils of the subtropics treated with organic materials. *Soil Biology & Biochemistry* **37**: 1507–1518.
- Khalil MI, Van Cleemput O, Boeckx P, Rosenani AB. 2001. Nitrogen transformations and emission of greenhouse gasses from three acid soils of humid tropics amended with N sources and moisture regime. I. Nitrogen transformations. *Communications in Soil Science and Plant Analysis* **32**: 2893–2907.

- Lakhdar A, Rabhi M, Ghnaya T, Montemurro F, Jedidi N, Abdely C. 2009. Effectiveness of compost use in salt-affected soil. *Journal of Hazardous Materials* **171**: 29–37.
- Lambers H. 2003. Dryland salinity: a key environmental issue in southern Australia. *Plant and Soil* **257**: 5–7.
- Laura RD. 1974. Effects of neutral salts on carbon and nitrogen mineralization of organic matter in soil. *Plant and Soil* **41**: 113–127.
- Laura RD. 1975. The role of protolytic action of water in the chemical decomposition of organic matter in soil. *Pédologie* **25**: 159–170.
- Laura RD. 1976. Effects of alkali salts on carbon and nitrogen mineralization of organic matter in soil. *Plant and Soil* **44**: 587–596.
- Li M, Jiang L, Sun Z, Wang J, Rui Y, Zhong L, Wang Y, Kardol P. 2012. Effects of flue gas desulfurization gypsum by-products on microbial biomass and community structure in alkaline–saline soils. *Journal of Soils and Sediments* **12**: 1040–1053.
- Macci C, Doni S, Peruzzi E, Mennone C, Masciandaro G. 2013. Biostimulation of soil microbial activity through organic fertilizer and almond tree association. *Land Degradation & Development*. DOI: 10.1002/ldr.2234.
- Mavi MS, Marschner P. 2012. Drying and wetting in saline and saline-sodic soils—effects on microbial activity, biomass and dissolved organic carbon. *Plant and Soil* **355**: 51–62.
- Mavi MS, Marschner P, Chittleborough DJ, Cox JW, Sanderman J. 2012. Salinity and sodicity affect soil respiration and dissolved organic matter dynamics differentially in soils varying in texture. *Soil Biology & Biochemistry* **45**: 8–13.
- McClung G, Frankenberger WT, Jr. 1987. Nitrogen mineralization rates in saline vs salt amended soils. *Plant and Soil* **104**: 13–21.
- McCormick RW, Wolf DC. 1980. Effect of sodium chloride on CO₂, evolution ammonification, and nitrification in a sassafras sandy loam. *Soil Biology & Biochemistry* **12**: 153–157.
- Muhammad S, Muller T, Joergensen RG. 2006. Decomposition of pea and maize straw in Pakistani soils along a gradient in salinity. *Biology and Fertility of Soils* **43**: 93–101.
- Muhammad S, Muller T, Joergensen RG. 2007. Compost and P amendments for stimulating microorganisms and maize growth in a saline soil from Pakistan in comparison with a nonsaline soil from Germany. *Journal of Plant Nutrition and Soil Science* **170**: 745–751.
- Muneer M, Oades JM. 1989a. The role of Ca organic interactions in soil aggregate stability. I Laboratory studies with ¹⁴C-glucose, CaCO₃ and CaSO₄·2H₂O. *Australian Journal of Soil Research* **27**: 389–399.
- Muneer M, Oades JM. 1989b. The role of Ca organic interactions in soil aggregate stability- II Field studies with ¹⁴C labelled straw. CaCO₃ and CaSO₄·2H₂O. *Australian Journal of Soil Research* **27**: 401–409.
- Naidu RP, Rengasamy P. 1995. Ion interactions and constraints to plant nutrition in Australian sodic soils. In *Australian sodic soils: distribution, properties and management*, Naidu R, Sumner ME, Rengasamy P (eds). CSIRO: Melbourne; 127–137.
- Nannipieri P, Ascher J, Ceccherini M, Landi L, Pietramellara G, Renella G. 2003. Microbial diversity and soil functions. *European Journal of Soil Science* **54**: 655–670.
- Nannipieri P, Giagnoni L, Renella G, Puglisi E, Ceccanti B, Masciandaro G, Fornasier F, Moscatelli MC, Marinari S. 2012. Soil enzymology: classical and molecular approaches. *Biology and Fertility of Soils* **48**: 743–762.
- Nelson PN, Oades JM. 1998. Organic matter, sodicity and soil structure. In *Sodic soils: distribution, properties, management and environmental consequences. Topics in sustainable agronomy*, Sumner ME, Naidu R (eds). Oxford University Press: New York, USA; 51–75.
- Nelson PN, Ladd JN, Oades JM. 1996. Decomposition of ¹⁴C-labelled plant material in a salt-affected soil. *Soil Biology & Biochemistry* **28**: 433–441.
- Nelson PN, Barzegar AR, Oades JM. 1997. Sodicity and clay type: influence on decomposition of added organic matter. *Soil Science Society of America Journal* **61**: 1052–1057.
- Nelson PN, Baldock JA, Oades JM. 1998. Changes in dispersible clay content, organic carbon content, and electrolyte composition following incubation of sodic soil. *Australian Journal of Soil Research* **36**: 883–897.
- Oren A. 1999. Bioenergetic aspects of halophilism. *Microbiology and Molecular Biology Reviews* **63**: 334–348.
- Oren A. 2002. Diversity of halophilic microorganisms: environments, phylogeny, physiology and applications. *Journal of Industrial Microbiology & Biotechnology* **28**: 56–63.
- Oren A, Steinberger Y. 2008. Coping with artifacts induced by CaCO₃–CO₂–H₂O equilibria in substrate utilization profiling of calcareous soils. *Soil Biology & Biochemistry* **40**: 2569–2577.
- Pan C, Liu C, Zhao H. 2013. Changes of soil physico-chemical properties and enzyme activities in relation to grassland salinization. *European Journal of Soil Biology* **55**: 13–19.
- Pandey VC, Singh K, Singh B, Singh RP. 2011. New approaches to enhance eco-restoration efficiency of degraded sodic lands: critical research needs and future prospects. *Ecological Restoration* **29**: 322–325.
- Pathak H, Rao DLN. 1998. Carbon and nitrogen mineralization from added organic matter in saline and alkali soils. *Soil Biology & Biochemistry* **30**: 695–702.
- Qadir M, Oster JD, Schubert S, Nobel AD, Sahrawat KL. 2007. Phytoremediation of sodic and saline sodic soils. *Advances in Agronomy* **96**: 197–247.
- Quails RG, Raines BL. 1992. Biodegradability of dissolved organic matter in forest through fall, soil solution, and stream water. *Soil Science Society of America Journal* **56**: 578–586.
- Rao DLN, Pathak H. 1996. Ameliorative influence of organic matter on biological activity of salt affected soils. *Arid Soil Research Rehabilitation* **10**: 311–319.
- Rao MA, Violante A, Gianfreda L. 2000. Interaction of acid phosphatase with clays, organic molecules and organo-mineral complexes: kinetics and stability. *Soil Biology & Biochemistry* **32**: 1007–1014.
- Rengasamy P. 2006a. Soil salinity and sodicity. In *Growing crops with reclaimed wastewater*, Stevens D (ed.). CSIRO: Australia; 125–138.
- Rengasamy P. 2006b. World salinization with emphasis on Australia. *Journal of Experimental Botany* **57**: 1017–1023.
- Rengasamy P. 2008. Salinity in the landscape: a growing problem in Australia. *Geotimes* **53**: 34–39.
- Richards L. 1954. *Diagnosis and improvement of saline and alkali soils*. Agricultural Handbook No. 60. US Department of Agriculture: Washington, DC.
- Rietz DN, Haynes RJ. 2003. Effects of irrigation-induced salinity and sodicity on soil microbial activity. *Soil Biology & Biochemistry* **35**: 845–854.
- Rousk J, Elyaagubi FK, Jones DL, Godbold DL. 2011. Bacterial salt tolerance is unrelated to soil salinity across an arid agroecosystem salinity gradient. *Soil Biology & Biochemistry* **43**: 1881–1884.
- Rukshana F, Butterly CR, Baldock JA, Xu JM, Tang C. 2012. Model organic compounds differ in priming effects on alkalinity release in soils through carbon and nitrogen mineralisation. *Soil Biology & Biochemistry* **51**: 35–43.
- Rukshana F, Butterly CR, Xu JM, Baldock JA, Tang C. 2013. Soil organic carbon contributes to alkalinity priming induced by added organic substrates. *Soil Biology & Biochemistry* **65**: 217–226.
- Schmidt MWI, Margaret ST, Samuel A, Thorsten D, Georg G, Ivan AJ, Markus K, Ingrid K-K, Johannes L, David ACM, Nannipieri P, Rasse DP, Weiner S, Trumbore SE. 2011. Persistence of soil organic matter as an ecosystem property. *Nature* **478**: 49–56.
- Setia R, Marschner P. 2013a. Impact of total water potential and varying contribution of matric and osmotic potential on carbon mineralization in saline soils. *European Journal of Soil Biology*. In press. DOI: 10.1016/j.ejsobi.2013.02.003.
- Setia R, Marschner P. 2013b. Carbon mineralization in saline soils as affected by residue composition and water potential. *Biology and Fertility of Soils*. DOI: 10.1007/s00374-012-0698-x.
- Setia R, Marschner P, Baldock J, Chittleborough D. 2010. Is CO₂ evolution in saline soils affected by an osmotic effect and calcium carbonate? *Biology and Fertility of Soils* **46**: 781–792.
- Setia R, Marschner P, Baldock J, Chittleborough D, Smith P, Smith J. 2011a. Salinity effects on carbon mineralization in soils of varying texture. *Soil Biology & Biochemistry* **43**: 1908–1916.
- Setia R, Marschner P, Baldock J, Chittleborough D, Verma V. 2011b. Relationships between carbon dioxide emission and soil properties in salt-affected landscapes. *Soil Biology & Biochemistry* **43**: 667–674.
- Setia R, Smith P, Marschner P, Baldock J, Chittleborough D, Smith J. 2011c. Introducing a decomposition rate modifier in the Rothamsted Carbon Model to predict soil organic carbon stocks in saline soils. *Environment Science and Technology* **45**: 6396–6403.
- Setia R, Smith P, Marschner P, Gottschalk P, Baldock J, Verma V, Setia D, Smith J. 2012a. Simulation of salinity effects on past, present, and future soil organic carbon stocks. *Environment Science and Technology* **46**: 1624–1631.
- Setia R, Setia D, Marschner P. 2012b. Short-term carbon mineralization in saline–sodic soils. *Biology and Fertility of Soils* **48**: 475–479.
- Shukla SK, Singh K, Singh B, Gautam NN. 2011. Biomass productivity and nutrient availability of *Cynodon dactylon* (L.) Pers. growing on soils of different sodicity stress. *Biomass and Bioenergy* **35**: 3440–3447.

- Singh BK, Millard P, Whiteley AS, Murrell JC. 2004. Unravelling rhizosphere-microbial interactions: opportunities and limitations. *Trends in Microbiology* **12**: 386–393.
- Singh K, Pandey VC, Singh B, Singh RR. 2012a. Ecological restoration of degraded sodic lands through afforestation and cropping. *Ecological Engineering* **43**: 70–80.
- Singh K, Singh B, Singh RR. 2012b. Changes in physico-chemical, microbial and enzymatic activities during restoration of degraded sodic land: ecological suitability of mixed forest over monoculture plantation. *Catena* **96**: 57–67.
- Singh K, Pandey VC, Singh RP. 2013a. *Cynodon dactylon*: an efficient perennial grass to revegetate sodic lands. *Ecological Engineering* **54**: 32–38.
- Singh K, Singh B, Tuli R. 2013b. Sodic soil reclamation potential of *Jatropha curcas*: a long term study. *Ecological Engineering* **58**: 434–440.
- Singh K, Singh B, Singh RR. 2013c. Effect of land rehabilitation on physicochemical and microbial properties of a sodic soil. *Catena* **109**: 49–57.
- Singh K, Trivedi P, Singh G, Singh B, Patra DD. 2015. Effect of different leaf litters on carbon, nitrogen and microbial activities of sodic soils. *Land Degradation & Development*. DOI: 10.1002/ldr.2313.
- Sinsabaugh RL, Moorhead DL. 1994. Resource allocation to extracellular enzyme production: a model for nitrogen and phosphorus control of litter decomposition. *Soil Biology & Biochemistry* **26**: 1305–1311.
- Sinsabaugh RL, Lauber CL, Weintraub MN, Ahmed B, Allison SD, Crenshaw C, Zeglin LH. 2008. Stoichiometry of soil enzyme activity at global scale. *Ecology Letters* **11**: 1252–1264.
- Sommer SG, Ersbøll AK. 1996. Effect of air flow rate, lime amendments, and chemical soil properties on the volatilization of ammonia from fertilizers applied to sandy soils. *Biology and Fertility of Soils* **21**: 53–60.
- Sumner ME. 1993. Sodic soils: new perspectives. *Australian Journal of Soil Research* **31**: 683–750.
- Sumner ME. 1995. Sodic soils: new perspectives. In *Australian sodic soils: distribution, properties and management*, Naidu R, Sumner ME, Rengasamy P (eds). CSIRO: Melbourne; 1–34.
- Sumner M, Rengasamy P, Naidu R. 1998. Sodic soils: a reappraisal. In *Sodic soil: distribution, management and environmental consequences*, Sumner M, Naidu R (eds). Oxford University Press: New York, NY; 3–17.
- Tejada M, Garcia C, Gonzalez JL, Hernandez MT. 2006. Use of organic amendment as a strategy for saline soil remediation: Influence on the physical, chemical and biological properties of soil. *Soil Biology & Biochemistry* **38**: 1413–1421.
- Tripathi S, Kumari S, Chakraborty A, Gupta A, Chakrabarti K, Bandyopadhyay BK. 2006. Microbial biomass and its activities in salt-affected coastal soils. *Biology and Fertility of Soils* **42**: 273–277.
- Tripathi S, Chakraborty A, Chakrabarti K, Bandyopadhyay BK. 2007. Enzyme activities and microbial biomass in coastal soils of India. *Soil Biology & Biochemistry* **39**: 2840–2848.
- US Salinity Laboratory Staff. 1954. *Diagnosis and improvement of saline and alkali soils*. USDA Handbook No. 60. U.S. Government Printing Office: Washington, DC.
- Ventosa A, Nieto JJ, Oren A. 1998. Biology of moderately halophilic aerobic bacteria. *Microbiology and Molecular Biology Reviews* **62**: 504–544.
- Wang J, Bai Z, Yang P. 2012. Sodic soil properties and sunflower growth as affected by byproducts of flue Gas desulfurization. *PLoS ONE* **7**: 52437. DOI: 10.1371/journal.pone.0052437.
- Wang C, Wang G, Wang Y, Rashad R, Ma L, Hu L, Luo Y. 2015. Fire alters vegetation and soil microbial community in alpine meadow. *Land Degradation & Development*. DOI: 10.1002/ldr.2367.
- Wang W, Fang J. 2009. Soil respiration and human effects on global grasslands. *Global and Planetary Change* **67**: 20–28.
- Westerman RL, Tucker TC. 1974. Effect of salts and salts plus nitrogen-15-labelled ammonium chloride on mineralization of soil nitrogen, nitrification and immobilization. *Soil Science Society of America Proceedings* **38**: 602–605.
- Wiesmeier M, Steffens M, Mueller CW, Kolbl A, Reszkowska A, Peth S, Horn R, Kogel-Knabner I. 2012. Aggregate stability and physical protection of soil organic carbon in semi-arid steppe soils. *European Journal of Soil Science* **63**: 22–31.
- Wong VNL. 2007. The effects of salinity and sodicity on soil organic carbon stocks and fluxes. Thesis Submitted to the Australian National University.
- Wong VNL, Greene RSB, Murphy BW, Dalal RC, Mann S. 2005. Decomposition of added organic material in salt-affected soils. Regolith. Ten years of CRC LEME. CRC LEME, pp. 333–337.
- Wong VNL, Dalal RC, Greene RSB. 2008. Salinity and sodicity effects on respiration and microbial biomass of soil. *Biology and Fertility of Soils* **44**: 943–953.
- Wong VNL, Dalal RC, Greene RSB. 2009. Carbon dynamics of sodic and saline soils following gypsum and organic material additions: a laboratory incubation. *Applied Soil Ecology* **41**: 29–40.
- Wong VNL, Greene RSB, Dalal RC, Murphy BW. 2010. Soil carbon dynamics in saline and sodic soils: a review. *Soil Use and Management* **26**: 2–11.
- Wu X-H, Zhang H-S, Li G, Liu X-C, Qin P. 2012. Ameliorative effect of castor bean (*Ricinus communis* L.) planting on physico-chemical and biological properties of seashore saline soil. *Ecological Engineering* **38**: 97–100.
- Wu JP, Liu ZF, Sun YX, Zhou LX, Lin YB, Fu SF. 2013. Introduced *Eucalyptus urophylla* plantations change the composition of the microbial community in subtropical China. *Land Degradation & Development* **24**: 400–406. DOI: 10.1002/ldr.2161.
- Yan N, Marschner P. 2012. Response of microbial activity and biomass to increasing salinity depends on the final salinity, not the original salinity. *Soil Biology & Biochemistry* **53**: 50–55.
- Yan N, Marschner P. 2013. Microbial activity and biomass recover rapidly after leaching of saline soils. *Biology and Fertility of Soils* **49**: 367–371.
- Yao S, Qin J, Peng X, Zhang B. 2009. The effect of vegetation on restoration of physical stability of severely degraded soil in China. *Ecological Engineering* **35**: 723–734.
- Yuan B-C, Li Z-Z, Liu H, Gao M, Zhang Y-Y. 2007. Microbial biomass and activity in salt affected soils under arid conditions. *Applied Soil Ecology* **35**: 319–328.
- Zahir ZA, Malik MAR, Arshad M. 2001. Soil enzymes research: a review. *Online Journal of Biological Science* **1**: 299–307.
- Zahrán HH. 1997. Diversity, adaptation and activity of the bacterial flora in saline environments. *Biology and Fertility of Soils* **25**: 211–223.