THE RELATIONSHIP BETWEEN SALT-AFFECTED AGRICULTURAL SOILS AND THE POTENTIAL ROLE OF EARTHWORMS IN RESTORATION: A REVIEW

TAO, J.[1,3*] – CHEN, J.[2] – GU, W.[1,3]

[1]*School of National Safety and Emergency Management, Beijing Normal University, Beijing 100875, China*

[2]*Key Laboratory for Ecology and Pollution Control of Coastal Wetlands (Environmental Protection Department of Jiangsu Province) School of Environmental Science and Engineering, Yancheng Institute of Technology Yancheng 224051, China*

[3]*Academy of National Safety and Strategic Development, Beijing Normal University, Beijing 100875, China*

**Corresponding author*
e-mail: juntao@bnu.edu.cn

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Abstract. Agricultural soil salinization has negative impacts on food production, environmental health and socio-economic wellbeing. The restoration of salt-affected agricultural soils focuses not only on the mediation of physicochemical habitats for plant establishment and growth but also on biological habitats for ecological functions. Earthworms are recognized to be essential components of soil biota but have been neglected to a great extent in the restoration practice of salt-affected agricultural land. Here we review current restoration of salt-affected agricultural soils, how soil salinity affects earthworms, how earthworm may contribute to the restoration of salt-affected agricultural soils and how earthworm populations may be improved in salt-affected agricultural soils. The major points are the following (1) The restoration of salt-affected agricultural soils focused on not only the "bioindicators" of earthworms but also the "facilitators" of it, which may contribute to the sustainable improvement of restored soils. (2) Soil salinity decreased biomass, abundance and diversity of earthworms in different degree depending on earthworm categories and salt ion composition. (3) Earthworm could improve soil properties (e.g. soil salt content, pH and physical structure), which would contribute to the restoration of the salt-affected agricultural soils. (4) The application of high-quality organic residues enhances establishment and development of earthworm population in salt-affected agricultural soils, which are conducive to implementation of the role of earthworms.
Keywords: *ecological restoration, ecological engineer, soil salinity, organic residues application*

Introduction

Salt-affected soils are generally defined as that electrical conductivity of soil is greater than 4 dS/m. Soil salinization arising from either natural or human-induced causes leads to an increase in concentration of dissolved salts in the soil profile. Moreover, the growing world population add to the competition for fresh water and global warming had risen soil evaporation and rising seawater level may further exacerbate soil salinization in some coastal regions (Rozema and Flowers, 2008; Eckelmann et al., 2006; Wang and Li, 2012; Tsanis et al., 2016). More than 3% of total soil resources are currently salt-affected (FAO, 2020), which figure will continue growing at a rate of up to 2 Mha yr^{-1} (Singh, 2018). Currently, about 33% of irrigated agricultural land is already affected by salinization as a result of poor agricultural practices. It is estimated that 50% of the croplands worldwide will become salinized by

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2050 (Nachshon, 2018). The soil salinization has set serious risks to long-term agricultural sustainability (Pulido-Bosch et al., 2018). In salt-affected agricultural soils, salts (mainly Na^+ ions) result in the dispersion of clay particles leading directly to the breakup of aggregates and to poor soil structure (*Fig. 1*) (Tejada and Gonzalez, 2006; Choudhary et al., 2006), which limits water infiltration and salt leaching (Gharaibeh et al., 2010; Yu et al., 2010). The formation of salt-affected agricultural soils is considered the main factor leading to soil degradation (*Fig. 1*) which impairs food production, environmental health and socio-economic wellbeing (Rozema and Flowers, 2008; Ondrasek et al., 2011). Salinization effects on agriculture including decreased productivity, an increased risk for less tolerant species, and the loss of biodiversity (Church et al., 2013).

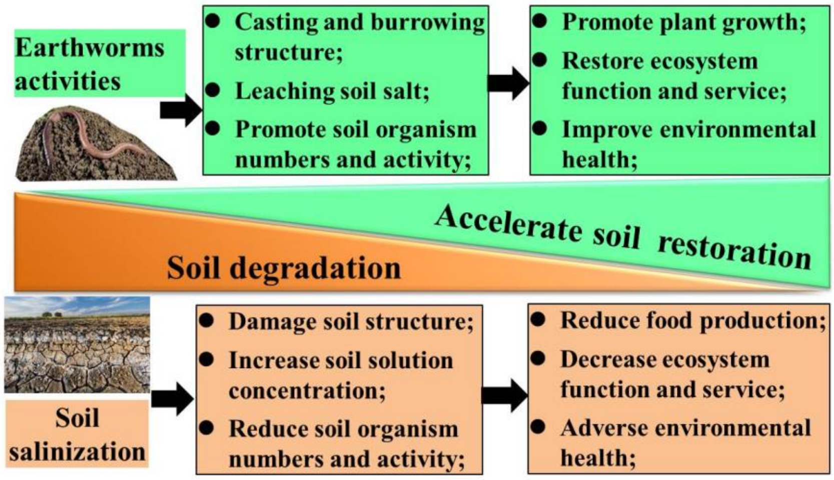

Figure 1. *Conceptual graph describing soil salinization change soil physical chemical and biological properties and consequently affect soil function productivity and environment. Earthworm applied into salt-affected soils improve soil structure leaching of salt and soil organism activity and consequently accelerate salt-affected soil restoration*

Soil organisms are essential to functioning of the soil ecosystems because they participate in key ecological processes like organic decomposition, nutrient cycling and maintenance of soil structure (Briones, 2014; Cohan et al., 2022). Soil fauna in various terrestrial ecosystems have received considerable attention in recent years due to their role in sustainable ecosystem functioning and services (Snyder and Hendrix, 2008; Blouin et al., 2013; van Groenigen et al., 2014; Bertrand et al., 2015). Earthworms are essential components of the fauna in temperate climates and are commonly regarded as ecosystem engineers (Lavelle et al., 1997). There is growing interest in how earthworms contribute to the improvement of the physical chemical and biological properties of the soil (*Fig. 1*) (Baker et al., 2006; Eriksen-Hamel and Whalen, 2007; De Oliverira et al., 2012) and the increase of plant production (Fonte et al., 2023). What roles earthworms might play in the ecological restoration of various degraded soils (Snyder and Hendrix, 2008; Butt, 2008; Boyer and Wratten, 2010; McDaniel et al., 2013; Duarte et al., 2014). The potential of earthworms to restore ecosystem function in salt-affected agricultural soils by improving soil and plant growth is an important future research topic.

In this review we focus on the restoration of salt-affected agricultural soils and the interaction between soil salinization and earthworms. This review first discusses recent

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research trends in the field of salt-affected land restoration. Second, we discuss the effect of soil salinization on earthworm abundance, biomass and ecological categories. We then discuss how the roles of earthworms in soils would contribute to the restoration of salt-affected agricultural soil and improve plant productivity. Finally, we also discuss how to increase earthworm abundance and biomass in salt-affected agricultural soil.

Restoration of salt-affected agricultural soils

Soil salinization causes a series of ecological and environmental issues such as soil deterioration rapid nutrient cycling and vegetation destruction which need to be addressed. Therefore, environmental criteria for restoration success after soil salinization are traditionally related to improvements in soil chemistry nutrient availability and crop yield (Tejada et al., 2006). Improvements to soil physical and chemical properties are essential for the restoration of most degraded agricultural land ecosystems and soil organisms can be manipulated to increase the speed of restoration (Harris, 2009). In earlier research most soil organism communities as “bioindicators” are gradually used to indicate the restoration state of the ecosystem (Callaham et al., 2008) and are usually well studied as “facilitators” in the recent decade especially soil fauna (Snyder and Hendrix, 2008; Boyer and Wratten, 2010). Attempts to restore other aspects of soil ecosystem function cannot succeed without a functioning soil ecological community (Heneghan et al., 2008). Therefore, increasing populations or addition of groups of soil fauna may be necessary to accelerate the restoration of soil ecosystem function in the restoration soils (Snyder and Hendrix, 2008) and in agricultural and reclaimed soils (Baker et al., 2006; Boyer and Wratten, 2010).

In salt-affected agricultural soils, one of the main soil environmental issues is the destruction of the soil structure which regulates water infiltration percolation and retention and material transfer (Romero-Aranda et al., 2001; Choudhary et al., 2006; Bottinelli et al., 2015). Moreover, improvements in porosity and aggregation can increase the soil’s capacity to retain moisture which reduces soil osmotic stress and consequently provides favorable conditions for the proliferation of plant roots and the activity of soil microorganisms (Paranychianakisa et al., 2004; Mavi and Marschner, 2012). For this reason, studies of salinized soil restoration are common (Tejada et al., 2006; Clark et al., 2007; Lakhdar et al., 2009) and often have the main aim of restoring soil structure (Snyder and Hendrix, 2008). Soil fauna are critical to the formation and stabilization of soil aggregates; they also create burrows and macropores that greatly facilitate the movement of water in the soil (Bottinelli et al., 2015). Many studies point to the importance of single dominant keystone organisms in determining soil aggregation and pore structure (Bastardie et al., 2003; Capowiez et al., 2012; Bottinelli et al., 2017). Additionally, many methods are used for the remediation of salt-affected agricultural soils which can improve soil physical and chemical properties and crop growth (Raychev et al., 2001; Rietz and Haynes, 2003; Tao et al., 2014; Tao et al., 2019). Moreover, the further improvement and sustainability of salt-affected soils may be obtained by increasing key soil organism population and diversity such as earthworms. It is well recognized that earthworms play an important role in mediating soil processes and functioning (Edwards, 2004; Blouin et al., 2013) by acting as soil engineers in soils (Jones et al., 1994; Lavelle et al., 1997). They can increase the decomposition and mineralization of organic residues by comminution incorporation and gut passage. Their burrowing and mixing activity results in the formation of

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macropores and aggregations influencing soil aeration and movement of water (Brown et al., 2000).

Interaction between salt-affected soil properties and earthworm ecotype

The impact of soil salinity on earthworms

Salt-affected agricultural soils in which salt concentrations are normally considered safe for many plants are known to have detrimental effects on soil earthworms (Owojori et al., 2009). Salinity as an individual parameter negatively affected earthworm survival and led to changes in earthworm individual biomass (McDaniel et al., 2013). The effects of soil salinity on earthworms could be attributed to the direct effects of the osmotic potential and the indirect effects of the food resources of earthworms (plant-derived materials and microorganisms) on earthworm abundance and biomass (Yuan et al., 2007; Wichern et al., 2006). A previous study in laboratory experiments showed that soil salinity (EC of 3.35 dS m^{-1}) decreased the dry biomass of earthworms (*Aporrectodea trapezoides)* and that soil salinity (EC of 7.35 dS m^{-1}) had adverse effects on the survival of earthworms in a salt-affected agricultural soil (Tao et al., 2012). In grassland, soil salinity (EC of 1.05 dS m^{-1}) decreased the abundance and biomass of earthworms under field conditions (Owojori and Reinecke, 2010). These results indicated that the changes of earthworm biomass were a more sensitive measure than the number of earthworms in the assessment of detrimental effects of soil salinity on earthworms in the short term. Additionally, soil salinity (EC of 0.52 dS m^{-1}) could reduce not only earthworm abundance and but also diversity of earthworm communities in meadows of the delta in the long term (Ivask et al., 2012).

Soil salinity also affected cocoon production. The study of Owojori et al. (2008) found that the salt content influencing cocoon production is lower than that influencing earthworm growth. Owojori et al. (2009) suggested that soil salinity caused a greater influence on earthworm survival than on earthworm reproduction at same salinity levels. A previous study showed that soil salinity (EC of 5.26 and 7.35 dS m^{-1}) had a significant effect on earthworm (*Aporrectodea trapezoides*) reproduction and caused the total cessation of reproduction in a coastal salt-affected agricultural soil (Tao et al., 2012). These results suggested that earthworm cocoon production of earthworms may be more sensitive to salinity than earthworm survival and biomass change of earthworms in the salt-affected agricultural soils (Raiesi et al., 2020). These results reinforce the idea that the increase in soil salinization likely led to a delayed effects on earthworm abundance (Pereira et al., 2019), which suggested a potential long-term impairment of the soil functions mediated by them. However, cocoons are commonly considered salt-resistant as well as drought- and stress-resistant and these characteristics maybe help to maintain earthworm survival with the decreasing of soil salinity (Holmstrup, 2001).

The impact of salt ion composition on earthworms

The effects of salinity on earthworms may be dependent on soil salt ion composition (Riet and Haynes, 2003; Owojori and Reinecke, 2010; Chen et al., 2017). In most studies on salinity the salt content of substrates is believed to be the main predictor of effects on earthworms but it is often measured without taking the soil salt composition into account (Owojori and Reinecke, 2014). In most studies on salinity the electrical

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conductivity (EC) of substrates is believed to be the main predictor of effects on soil organisms. However some studies have shown that salinity as measured by EC could not be used to correctly predict the effects of salt on soil organisms when comparing different saline areas (Riet and Haynes, 2003; Mavi et al., 2012). This limitation may be due to differences in anion and cation composition between different salt-affected agricultural soils. In saline soils from specific areas Ca was the dominant cation (Riet and Haynes, 2003). Ca salts led to obviously higher decreases in earthworm (*Eisenia fetida*) survival and weight than Na salts (Owojori and Reinecke, 2014). In greenhouse soil excessive water and fertilizer applications caused soil salinity with NO_3^- (Darwish et al., 2005; Shi et al., 2009) which may result in different effects on earthworms than soil salinity with Cl^- (Owojori and Reinecke, 2014). In future studies it should be considered how salt ion composition affects earthworm parameters.

The responses of earthworm ecological categories to soil salinity

Epigeic earthworms live close to the soil surface (topsoil); endogeic earthworms inhabit the deeper layers and consume large amounts of mineral soil; anecic earthworms feed on large organic material at the soil surface and inhabit the subsoil (Edward and Bohlen, 1996). Thus, the effects of soil salinization on earthworms would depend on ecological categories (Ivask et al., 2012). With respect to salt effects and distribution epigeic species may be more sensitive to the effects of salinity accumulating in the surface soil while endogeic species which feed and live within the soil would be less sensitive to the effects of surface salinity and anecic species might experience intermediate impacts. Epigeic earthworms were more tolerant to the limiting effects of salinity accumulated in the surface layer compared to other earthworm ecological categories (Ivask et al., 2007, 2012). The epigeic species *Dendrobaena octaedra Eiseniella tetraedra Dendrodrilus rubidus* and *Lumbricus castaneus* were present in subsaline and saline coastal zones (Keplin and Broll, 2010). However, a few studies suggested that epigeic earthworms (*Eisenia fetida*) appeared to be more sensitive responses to salinity than endogeic earthworms since the survival of epigeic earthworms was seriously affected (Owojori and Reinecke, 2009; Owojori et al., 2009) whereas no significant effect on survival was found for *Aporrectodea caliginosa* at this salinity level in natural saline soil (Owojori et al., 2009). However, the abundance of the endogeic species *Aporrectodea caliginosa, Aporrectodea rosea* and *Octolasion lacteum* were negatively affected by soil salinity in the coastal salt-affected agricultural soil of the Baltic Sea (Ivask et al., 2012). The growth of endogeic earthworms (*A. caliginosa*) was significantly affected by a lower salinity than the value that affected the growth of epigeic earthworms. These results suggest that the community tolerance of earthworms to soil salinity also depends on its ecological categories (Van Leeuwen and Vermeire, 2007; Pereira et al., 2019).

The role of earthworms in the restoration of salt-affected agricultural soils

Impact on soil salinity

The main objective of salt-affected soils is to reduce soil salinity, which alleviated the effects of it on plant growth, soil organism activity and soil structure. As some of the most important soil-dwelling organisms earthworms play a significant role in soil structure and water holding capacity improvement through their burrowing and casting

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activities (Görres et al., 2001; Capowiez et al., 2012; Bottinelli et al., 2017), which can influence the movement of soil water-salt. Salt in salt-affected agricultural soils leaches into deeper soil depths as earthworm activities improve the soil structure (Zhang et al., 2015). Earthworm casts also significantly altered the soil structure, which facilitate the leaching of salt ions, reducing the salt content of the topsoils (Li et al., 2021). The application of earthworms (*Eudrilus eugeniae*) combined with organic material (compost and vermicompost) could reduce soil salinity which may be because that the increasing Ca^{2+} and Mg^{2+} concentration in the soil solution permitted greater leaching of exchanged Na^{+} in percolating water (Oo et al., 2015). The studies of Zhang et al. (2016, 2018) also showed that epigeic earthworms (*Eisenia fetida*) could decrease soil salt concentration through the improvement of soil structure and water movement drainage in saline alkali soil. A previous study also showed that the presence of endogeic earthworms significantly increased leaching of salt from salt-affected agricultural soils under rainfall conditions (Wang et al., 2016). They speculated that earthworm burrowing activity created channels and improve the leaching of saline water (*Fig. 2*). The anecic species tend to inhabit semi-permanent vertical burrows in the soil which may have strong effects on soil water-salt movement. Different earthworm ecological categories have distinct burrow networks and consequently result to different patterns of soil water-salt movement. Moreover, the interactions between different ecological groups could alter the movement of solutes (Shuster et al., 2002; Ernst et al., 2009) and thereby create distinct patterns in water-salt transport.

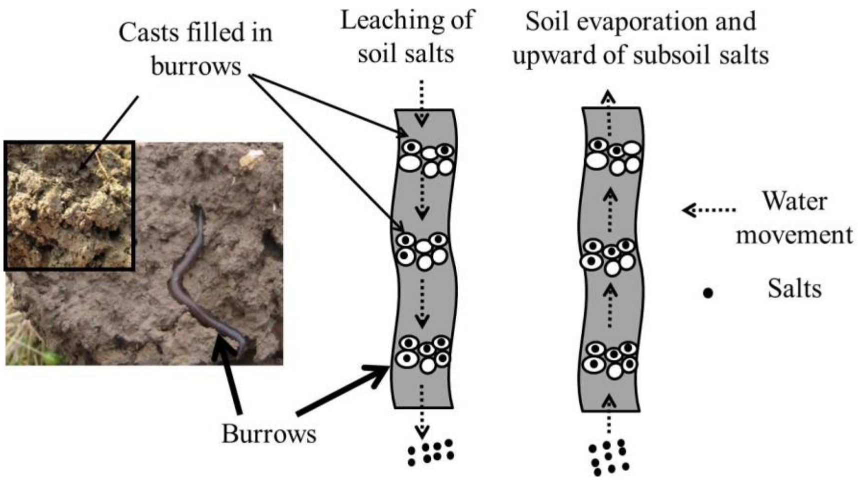

Figure 2. *Conceptual graph describing earthworm activities (casting and burrowing) promote the leaching of water and salt from salt-affected agricultural soil (photographs by Tao Jun). Additionally, earthworm decrease the water content of the upper soil layer (earthworm mainly live in this soil layer). Consequently, this process may also affect upward movement of water and salt from the subsoil layer without earthworms*

In addition, changes in soil structure due to earthworm burrowing and casting activity affected not only soil water infiltration and solution transfer but also soil evaporation and the upward movement of the soil solution (*Fig. 2*). The study of Lipiec et al. (2015) demonstrated that pore size distribution was different between earthworm casts and the surrounding soil. They found that the median and average pore radius were greater in earthworm casts than in the surrounding soil aggregates. The results of a

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previous study indicated that soil porosity was significantly decreased in earthworm casts compared to that in the surrounding soil aggregates (Jouquet et al., 2008). These differences may contribute to the significantly higher salt content in casts under evaporation than in the surrounding soils (Wang et al., 2016). The burrowing activities of anecic and endogeic earthworm species might result in stronger aeration of the topsoil. Consequently, larger biopores in the soil increased the gas exchange and thus increased the loss of water vapor from the soil (Ernst et al., 2009). A previous study indicated that earthworms decreased the water content of salt-affected agricultural soils under evaporation conditions (Wang et al., 2016). However, the study of Li et al. (2021) found that Earthworm casts increased the total porosity and capillary porosity of the soil, which likely increased the soil's water-holding capacity and lowered evaporation. These soil water processes may also affect upward movement of salts in salt-affected agricultural soil (*Fig. 2*). Therefore, at present the related systematic research on the effects of earthworms on salt distribution under evaporation conditions is rather limited.

Impact on soil pH

Soil pH has a considerable impact on controlling plant nutrients particularly the availability of micronutrients (Grattan and Grieve, 1992). Saline soil pH is significantly increased by salt leaching in salt-affected agricultural soil (Murtaza et al., 2006; Choudhary et al., 2006; Wang et al., 2012). These studies showed that the soil desalinization process of salt leaching by watering could cause soil alkalinization problems. Although most studies found that the pH in earthworm casts is higher than that in the surrounding soil (Versteegh et al., 2014; Vos et al., 2014) the pH in earthworm casts is lower than in the surrounding soils when the original pH of the soils is higher than 7 (Van Groenigen et al., 2019). A few studies have indicated that earthworms have the potential to decrease soil pH in salt-affected agricultural soils (Oo et al., 2015; Zhang et al., 2016, 2018). The effect of earthworms might be a result of the production of various organic acids by their gut microbes and the pH-homeostasis mechanisms of their gut tissue (Ravindran et al., 2014). These observations indicated that the presence of earthworms may mitigate negative salinity-pH relationships and thus reduce the risk of soil secondary alkalization.

Impact on plant growth

Soil salinization is one of the major causes of yield reduction in modern agriculture (Rozema and Flowers, 2008). Salt accumulation in the root zone affects plant performance directly through the development of osmotic potential and the disruption of cell ion homeostasis (Zhu, 2001; Munns, 2002) and indirectly through the limiting soil nutrient availability in the rhizosphere (Farooq et al., 2015). Earthworms are thought to have positive effects on plant growth in salt-affected soils (Zhang et al., 2016, 2018). The positive effects of earthworms on plant growth may be due to several possible mechanisms; these mechanisms included the enhancement of nutrient availability the improvement of soil structure the production of plant growth-regulating substances and the stimulation of microbial plant symbionts (Fonte et al., 2023). The first mechanism was firstly mentioned in previous studies. Especially in the salt-affected soils the decreases in the size and activity of soil microorganisms had a negative effect on microbiological processes and consequently impacted organic matter decomposition and nutrient availability (Qadir and Schuber, 2002; Yuan et al., 2007; Yan and

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Marschner, 2012). Earthworms can consume organic substrates and release nutrients into soil through metabolic processes and consequently affect soil nutrient cycling (Zhang et al., 2016). They found that earthworms significantly increased the abundance of *Pontibacter* in saline soil that contributed to the promotion of available P which was a contributing factor for plant growth (Dasager et al., 2011). Earthworms also increased the abundances of Trichoderma (plant-promoted fungi) in the saline soils (Zhang et al., 2016) which enhanced nitrogen uptake and promoted crop growth (Tanwar et al., 2013). Additionally, Oo et al. (2015) and Zhang et al. (2016) showed that earthworms enhanced soil microbial biomass catalase activity and basal respiration in salt-affected soils through their gut processes (Svensson and Friberg, 2007) which may increase total soil nutrient turnover and prevent crop from oxidative damages under salinity conditions. In salt-affected soils earthworm could affect plant pathogens (decreasing *Methylobacterium* abundance) and consequently promote crop growth as well in non-saline soils (Zhang et al., 2016).

In the salt-affected agricultural soils, organic residues can serve as food for earthworms (Tao et al., 2012; Chen et al., 2017) and earthworms can increase crop production by increasing N mineralization (Zhang et al., 2016). Earthworms could significantly increase nutrient and mineral elements uptake into plant shoot in salt-affected soils to improve crop salt tolerance which promote crop growth under saline stress (Rabie and Almadini, 2005; Shahzad et al., 2012). For example, an increase in the uptake of exchangeable K and Ca (in competition with sodium) by earthworms could increase crop biomass in saline soil (Zhang et al., 2018). Earthworm could improve crop photosynthetic and osmoprotectants by increase the Mg and N content of shoot in salt-affected soils which may promote crop growth under saline conditions (Anjum et al., 2014; Porcel et al., 2015). Additionally, the beneficial effects of earthworms on plant growth may be due to the restoration of demolished soil structure destroyed by salinity. Some previous studies suggested that the presence of earthworms increased plant biomass in the disturbed soils compared to that in the undisturbed soils (Spurgeon et al., 2013; Van Groenigen et al., 2014). In salt-affected soils earthworms could increase soil macroaggregates proportions, stability of aggregates and macropores numbers under mesocosm experiment which contributed to enhancement of crop growth (Kou et al., 2023). However, it may be difficult to distinguish the effects of the improved soil structure from those of increased nutrient availability when earthworms are present in the salt-affected agricultural soils. Apart from the previously mentioned mechanisms the effects of earthworms on plant growth in salt-affected agricultural soil may be partly attributed to the reductions in the root zone soil salt concentration which is leached downward to deeper soil layers (Kou et al., 2023).

Enhancement of earthworm populations in salt-affected agricultural soils

Earthworms that are able to recolonize or enhance in a salt-affected agricultural soil are important for soil restoration. Numerous studies have shown accelerated the recolonization and enhancement of earthworms following organic matter amendments of base restoration soil (Lowe and Butt, 2002; Hurisso et al., 2011; Wu et al., 2013). As discussed in the previous studies (Eijsackers, 2011) an important factor for earthworm recolonization and population growth in these various degraded soil habitats is soil organic carbon which enables earthworm survival and growth. However, in salt-affected arable land the amounts of organic carbon in the soil tend to decrease which does not

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support earthworm population growth. Various organic residues (e.g., plant residues, manures, biosolids and composts) have been applied to salt-affected agricultural soil to maintain soil organic carbon and improve soil physical chemical and microbial properties (Tejada et al., 2006; Liang et al., 2005; Lakhdar et al., 2009). The extent to which earthworm population growth and species diversity increases in a salt-effected agricultural soil as well as in other restored soils would be likely to depend on agricultural management practices such as organic matter application (Wu et al., 2001). The study of Qiao et al. (2001) concluded that management practices (mainly the input of organic material) which gradually reduces the salt concentrations are conditions suitable for earthworm recolonization and population growth in field.

The application of organic residues increased the growth of endogeic earthworms in salt-affected agricultural soil and significantly promoted their reproduction in the soils with the low salinity (Tao et al., 2012). Therefore, they explained that the amendment with organic residues might improve soil quality and food sources for earthworms including the available substances and microbial biomass. In addition, the quality and composition of organic residues applied to the soil influences soil organic carbon and consequently benefits earthworms. The biochemical composition of organic residues such as the carbon to nitrogen ratio of residues could be considered as a qualitative indicator of the food resources supplied to earthworms (Cesarz et al., 2016). The study of Chen et al. (2017) suggested that the input of low C/N residues (clover plants) into salt-affected agricultural soil increased earthworm growth and reproduction compared to that under high C/N residues (wheat plants) in the coastal region of Bohai Bay in China. The results of this experiment are in agreement with those of a previous study (Fraser and Piercy, 1998) in which amendment with clover residues significantly increased earthworm population. This may be because that the low C/N residue application has a significantly higher decomposition rate than the high C/N residues. On the other hand, the decomposition of low C/N residues could produce a higher concentration and longer lasting source of water-extractable organic C (Hasbullah and Marschner, 2015) which can be easily taken up by soil microbes and earthworms (Hasbullah and Marschner, 2016). Moreover, the higher N concentration in residues could improve the production of osmolytes (such as proline and glycine betaine) by providing N for their synthesis (Saum and Müller, 2007) which consequently supported earthworm growth and reproduction (Whalen and Parmelee, 1999; Curry and Schmidt, 2007). The decomposition of high C/N residues requiring greater energy for synthesis and release of enzymes (Uchida et al., 2012) is slow in a salt-affected agricultural soil (Setia and Marschner, 2013). In field conditions, the study of Chen et al. (2022) also observed a higher earthworm biomass in salt-affected agricultural soil with clover residues than that in the same soils without clover residues. Moreover, the latest research suggested that animal residue applied into a salt-affected agricultural soil significantly enhanced earthworm (endogeic species) population and biomass compared to plant residues in mesocosms of field (Chen et al., 2022). They explained that the application animal residue obtained a higher soil available resources and nutrients than clover residues (Nguyen et al., 2018; Naveed et al., 2021), which contribute to the increase in earthworm growth in the salt-affected soils. This result showed that to promote field survival and biomass of earthworms in a salt-affected agricultural soil, animal manure application may be a critical important amendment.

In addition to organic residue inputs for the benefit of earthworms, soil moisture is also considered to be a key environmental factor for determining earthworm numbers

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growth reproduction and activity (Holmstrup, 2001; Perreault and Whalen, 2006) especially in salt-affected agricultural soils (Tao et al., 2013). Soil moisture conditions can change the response of earthworm growth and reproduction to soil salinity (Ivask et al., 2012). High soil moisture content contributed to higher earthworm biomass and numbers (Eriksen-Hamel and Whalen, 2006). For example, endogeic species preferred high moisture conditions and were present in high numbers in floodplains (Zorn et al., 2008). High soil moisture content (95% field capacity) significantly increased the dry weight and numbers of earthworm compared to the low soil moisture content (75% field capacity) in a salt-affected agricultural soil in a laboratory experiment (Chen et al., 2017). This result may have occurred for several reasons (1) the decrease in the osmotic potential of soil solution (Setia and Marchner, 2013) could have benefited earthworm growth; (2) the increase in transport of soluble substrates (Poll et al., 2008) contributed to higher earthworm consumption and assimilation; or (3) other available organic matter increased earthworm growth (Leroy et al., 2008; Butt, 2011). Additionally, the high soil moisture content increased the number of cocoons compared to those at a low moisture content in a salt-affected agricultural soil (Chen et al., 2017). This result indicated that high soil moisture content promoted earthworm reproduction, which might affect earthworm population over a period of time.

Moreover, the increase in earthworm populations as a restoration agent requires careful consideration of the location of the restoration project. Restoration practitioners must ask themselves “Whether there are earthworms in the restoration region”, “Which earthworm species should be supported?” Meanwhile restoration goals for earthworm populations must take into account the location’s native earthworm species. A previous study found that the earthworm *Aporrectodea trapezoides* appears to be the dominant species in salt-affected agricultural soils in the coastal region of China’s Bohai Bay (Tao et al., 2013) and has the greatest potential for colonization of the salt-affected agricultural soils in this region (Tao et al., 2012). Further research should focus on the potential enhancement of native earthworm species in salt-affected agricultural sites (Lavelle et al., 1999).

Conclusions

Earthworms are a key functional group of soil organisms that are affected by soil salinity depending on their ecological categories and stages of development in salt-affected agricultural soils. In the salt-affected soils much previous research has focused on the changes of earthworm communities as bio-indicators of soil improvement. Although this function as an indicator is related to their potential use in restoration it is not strictly an ecosystem service. Future research should focus on understanding the use of earthworms to modify soil function and provide ecosystem services in the salt-affected agricultural soils. For example, the study of the relationship between earthworm burrows and water-salt movement would help to explain soil salt leaching and upward movement and the resulting distribution of salt in the soil profile. These soil processes are important for plant growth and successful ecosystem restoration in salt-affected lands. In addition, the colonization or recovery of earthworm population numbers and communities is the foundation for restoration of soil and the re-establishment of ecosystem function. Therefore, future research should therefore advance more management practices (e.g., various organic residue applications) that increase earthworm populations and growth in the salt-affected agricultural soil systems

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or that help earthworm return to the disturbed lands because the presence of earthworms stimulates plant production and will help to narrow the productivity gap between salt-affected agricultural soils and non-salt-affected agricultural soils.

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