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A novel evaluation of the effect of lanthanum exposure on plant populations

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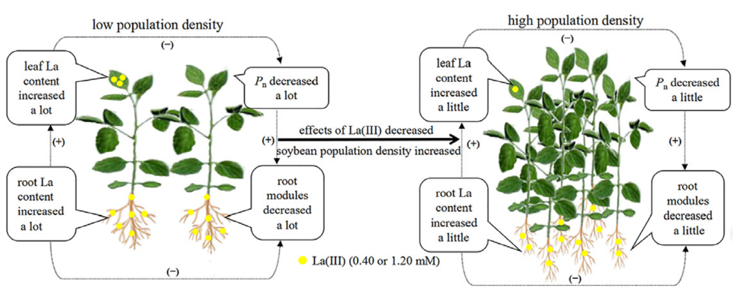
HIGHLIGHTS

- A new experiment at plant population scale was designed to evaluate effects of REEs.
- La (III) effects on the root modules varied with soybean population density.
- It was proved that changes in root modules were related to photosynthesis.
- It was proved that changes in photosynthesis were related to La content in plants.

GRAPHICAL ABSTRACT



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ABSTRACT

The accumulation of rare earth elements (REEs) in the environment has recently become a new environmental problem. There have been many studies about the effects of REEs on plant at the individual, organ, cellular and genetic levels. Plants exist in populations under natural conditions, but little is known about the effects of REEs on plant populations. In this study, the effects of lanthanum (III) [La(III)] on the root module growth of soybean (*Glycine max* L) populations at different densities were investigated by simulating La(III) pollution. Results showed that at La(III) concentrations of 0.40 and 1.20 mM, both the root module growth parameters and leaf photosynthesis parameters were decreased, with 1.20 mM of La(III) causing a more significant decrease. In addition, the above parameters in low-density soybean populations decreased more significantly than those in high-density soybean populations. The above results show that the inhibitory effects of 0.40 and 1.20 mM of La(III) on the growth of root modules are closely related to the inhibition of photosynthesis in soybean population. Moreover, the inhibitory effect of La(III) on the growth of root modules of soybean population is enhanced as the La(III) concentration increases, while is weakened as plant population density increases. This study would provide a reference for the further research on the ecotoxicology of REEs, and show a new perspective and basis for the objective assessment of the environmental risks of REEs.

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One sentence summary: La(III) pollution affects the root module growth and photosynthesis in soybean populations, and the effects vary depending on soybean population densities.

1. Introduction

Due to their special physical and chemical properties, rare earth elements (REEs) are widely used in many fields, such as electronics, petrochemicals, military, agriculture, and medicine (Zhao et al., 2008; Zhang and Shan, 2001; Loell et al., 2011; Alonso et al., 2012; Dutta et al., 2016). In China, rare earth mining and the long-term use of REEs in agriculture have led to the continuous rise of REE concentrations in the environment (Zhang and Shan, 2001; Wang et al., 2011; Sun et al., 2013a, b). For example, in the soil of the Baiyun Obo mining area REEs have been detected at concentrations as high as 27549.58 mg kg^{-1} (Li et al., 2008; Liang et al., 2014; Hao et al., 2015). Similarly, average REE concentrations in the water, suspended particles, and sediment of the Sidaosha River in Inner Mongolia were 3826 μg L^{-1}, 31524 mg kg^{-1} and 30461 mg kg^{-1}, respectively (Liang et al., 2014). Furthermore, in other developing and developed countries, REEs are heavily used as "raw materials" in high-tech industries (Ramos et al., 2016a; Tukker, 2014), thus they have been increasingly accumulating in the environment (Ramos et al., 2016b). Current reports have indicated that REEs in global non-mining areas have an average maximum concentration of 316 mg kg^{-1} (Cape Verde) and a minimum of 32 mg kg^{-1} (Denmark) (Ramos et al., 2016b). Therefore, REE accumulation has become a new environmental safety risk (Wang et al., 2000; Zhu et al., 2005; Giovanni et al., 2015). Previous studies have shown that REEs can be absorbed from the environment by edible plants and amplified step by step along the food chain (Wang et al., 2000), accumulating in organs such as bones, livers, and kidneys (Zhu et al., 2005), causing multi-system and multifunctional damage, and threatening the human health and safety (Giovanni et al., 2015). Therefore, although REEs are essential in many industrial applications, the effects of REEs on humans and the environment should be further characterized to definitively determine the environmental safety, food safety and human health issues caused by REEs.

Plants are primary producers and thus play crucial roles in ecosystems (Cardinale et al., 2011). Therefore, studying the effects of pollutants on plants can provide important information that can be further used in ecosystem risk assessment (Coelho et al., 2009). There have been many studies focused on the impacts of environmental REEs on plants (Paola et al., 2007; D'Aquino et al., 2009; Sun et al., 2013a, b; Wang et al., 2014b; Carpenter et al., 2015; Hu et al., 2016; Xia et al., 2017; Zhang et al., 2017). For example, it has been reported that low-concentration La(III) can promote wheat root growth, while medium and high concentrations of La(III) can inhibit wheat root growth (D'Aquino et al., 2009). Other studies have shown that high-concentration La(III) can affect soybean seedling root phenotype (Sun et al., 2013a, b), inhibit soybean root nitrogen assimilation processes (Zhang et al., 2017), affect rice photosynthesis (Wang et al., 2014b), damage chloroplast ultrastructure, and reduce the mineral elemental content of rice (Hu et al., 2016). Moreover, Wang et al. found that rare earth elements can initiate endocytosis in plants (Wang et al., 2014a), and Xia et al. found that La(III) can affect soybean nitrate reductase gene transcription (Xia et al., 2017). All these prior studies are focused on effects at the organ, cellular, and genetic levels. However, in both natural and man-made environments, plants exist in populations (Long and Vacchiano, 2014). Thus, REEs are more likely to act on entire plant populations, rather than on individual plant. Therefore, there is a need to characterize the effects of REEs on plants at the level of population.

It is now clear that plant population density can affect the state of plant growth, which affects both the plant population's use of environmental resources and the competitiveness of the plant population (Fasoula and Tollenaar, 2005; Springer and Gillen, 2007; Zhang et al., 2014). However, some questions remain. First, do REEs affect the growth status of plant population? Second, how do REEs affect the growth status of plant population? Based on previous studies (Sun et al., 2013a, b; Zhang et al., 2017), this study simulated La(III) pollution at two lethal doses (0.40 and 1.20 mM). According to common planting densities of soybeans (Ryan and Curran, 2011; Javier de Luca et al., 2014), and accounting for research needs, we used four densities (10, 20, 30 and 40 plant pot^{-1}) of soybean population in this study. Soybean, an important food crop recommended by the US Environmental Protection Agency (EPA) for toxicological research (Nordborg et al., 2014), was selected as the test organism for this study. We studied the effects of La(III) exposure on the root module growth and photosynthesis of soybean populations. Furthermore, we determined how La(III) exposure affected La content in the soybean plants. The purpose of this study was to characterize the effects and mechanisms of action of La(III), a kind of rare earth element, on the growth status of root module of soybean population at different densities, to provide a reference for environmental risk assessment of REEs and provide a theoretical basis for the further research on the ecotoxicology of REEs.

2. Materials and methods

2.1. Crop culture and La(III) treatment

To eliminate pathogenic microorganisms and prevent soybean pests and diseases, experimental soybean seeds (Zhonghuang 25, Wuxi Seed Co., Ltd., China) were surface sterilized with 0.1% $HgCl_2$ for 5 min and rinsed three times with deionized water (Sun et al., 2013a, b; Zhang et al., 2017). Soybean seeds were then soaked in deionized water for 24 h and germinated in a thermostatic incubator (25 ± 1.0 °C) with deionized water replenished on time. When the radicle reached 2 cm in length, in order to reduce the interference of soil medium (such as organic/inorganic pollutants, mineral nutrients, microorganisms and so on) on the content of La(III) in soil medium and soybean root modules, we used the hydroponics commonly used in the simulated pollution experiments to plant soybean population (Ferrara et al., 2006; Finger-Teixeira et al., 2010; Oliveira et al., 2015). The germinated soybeans were aquatically cultured in pots (320 × 215 × 15 mm) in a greenhouse (temperature: 25 °C, light intensity: 300 μmolm^{-1} s^{-1}, photoperiod: 16 h/8 h) (Hu et al., 2016). Foam boards (320 × 215 × 15 mm) with 10, 20, 30 and 40 holes (diameter = 1 cm) were used to control the soybean population densities. Each hole was planted with one soybean plant. Deionized water was replenished daily. When the first true leaf was unfolded, the soybean populations were cultured with 1/2 Hoagland nutrient solution (Hoagland, 1920), and the nutrient solution was replaced every 3 days. After 30 days, the