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Nitrogen cycling in the soil–plant system along a series of coral islands affected by seabirds in the South China Sea

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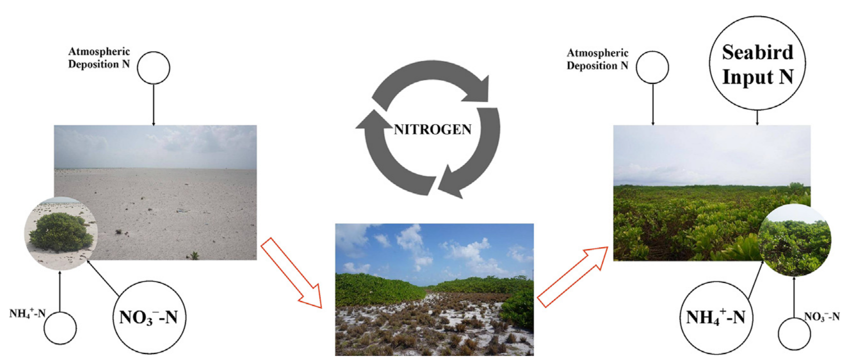
HIGHLIGHTS

- Vegetation cover is related to N content in soils and thus seabird guano input.
- When few seabirds inhabit islands, the main source of N is atmospheric deposition.
- As seabird numbers increase, guano becomes the main N source on the islands.
- More NH_4^+-N is used by plants with increased inputs from seabirds.

GRAPHICAL ABSTRACT



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ABSTRACT

The nitrogen (N) utilization strategy of plants has become a topic of interest within the field of phytoecology. However, few studies have considered N cycling on coral island ecosystems from the perspective of their evolution. The aim of this study was to test the impacts of biological transport by seabirds, on the sources and uses of N by plants, and pathways of N cycling in soil–plant ecosystems on coral islands. A series of eight coral islands were investigated, five of which were affected to a varying extent by seabirds. The total phosphorus (TP) concentration from avian sources and the $\delta^{15}N$ values of total nitrogen (TN) and inorganic nitrogen (IN: NH_4^+-N, and NO_3^--N), $\delta^{18}O$ of NO_3^--O, in soils were determined, as well as proxies in plant leaves of two dominant plant species, including TN, the carbon/nitrogen ratio (C/N), and $\delta^{13}C$ and $\delta^{15}N$ values. The results show that, with an increase of TP, the TN and IN content, and $\delta^{15}N$ values in soils all increased. Plant C/N and $\delta^{15}N$ values decreased and increased, respectively, as the soil N content increased. When the TN content of the soil was low, the $\delta^{15}N$ value in plant leaves was similar to that in soil NO_3^-, but was much lower than that in soil NH_4^+. When the soil TN content was high, the $\delta^{15}N$ values were similar. Both plants and soil were probably N-limited prior to seabird colonization, with the N source on the barren coral islands originating primarily from atmospheric deposition. With seabird guano input and subsequent pedogenesis, the source of N switched to guano. Under these conditions, most of the N utilized by plants originated from NH_4^+, while nitrate is dominant for non-seabirds islands. Seabird activities have played a key role in the N dynamics of soil–plant ecosystems at coral islands.

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1. Introduction

As one of the most important circulation processes on the Earth's surface, nitrogen (N) cycling has received increasing attention in recent years. N cycling, which is the transformation and flow process of nitrogen, has long been present in natural systems, including atmosphere, hydrosphere, pedosphere and biosphere. These natural processes have been supplemented or replaced by anthropogenic drivers such as intensive agriculture (e.g., fertilizer use), urbanization and fossil fuel combustion (Galloway et al., 2008; Fowler et al., 2013; Saggar et al., 2013; Badagliacca et al., 2018). Many environmental issues are closely related to imbalances in the N cycle, such as photochemical smog (Logan, 1983), acid rain (Likens and Bormann, 1974), lake and river eutrophication (Anderson et al., 2002), eutrophication of forests, soil acidification, and a change from N-limitation to phosphorus (P)-limitation in biological processes (Wassen et al., 2005; Lu et al., 2014). N cycle in plant–soil ecosystems at regional and global scales has become a focus of ecological research (Wang et al., 2014; Díaz et al., 2016). However, a complex and diverse range of responses have been reported in such studies. To understand the internal mechanisms of the N cycle and predict possible future changes, large scale investigations within different ecosystems are required.

Stable isotope analysis is a robust technique that can be applied in investigations of the N cycle (Robinson, 2001; Fry, 2006; Casciotti, 2016), and more specifically can be used to trace matter cycling, compare temporal and spatial ecological processes, indicate the existence and level of key ecological process, and record the responses of organisms to global environmental change. Naturally occurring $^{15}N/^{14}N$ is the most common indicator used in such studies to trace soil N sources (e.g., Brenner et al., 2001). The $\delta^{15}N$ values in different N species can sometimes be used to analyze plant N sources and preferences (Kahmen et al., 2008; X.Y. Liu et al., 2014). In addition, the increasing N concentration and $\delta^{15}N$ values in leaves can be indicative of regional increases in N availability due to anthropogenic N deposition in tropical forests (Hietz et al., 2011). Recently, J. Liu et al. (2017) found that $\delta^{15}N$ values in plants, soil total N (TN), and soil NO_3^- would significantly increase as a result of N addition, while the $\delta^{15}N$ value of soil NH_4^+ was not significantly changed and the $\delta^{15}N$ value of soil N_2O significantly decreased. Overall, plant $\delta^{15}N$ values are related to those of soil, but are dramatically influenced by physiological mechanisms and the external environment (Evans, 2001; Amundson et al., 2003). Thus, we can better understand N dynamics by combining both plant and soil $\delta^{15}N$ values.

Biological transport, which means higher animals transport materials to higher potential energy, has an impact on N cycling in remote areas. In many cases seabirds are important transport agents (Hobara et al., 2005; Nie et al., 2012; Szpak et al., 2012; Hawke and Condron, 2014). Apart from wetland (e.g., Litaor et al., 2016), this process is most likely to occur on marine islands (Erskine et al., 1998; Adame et al., 2015). Mulder et al. (2011) detailed seabird island ecosystems, compared relevant ecological studies such as the impact of seabird colonies on biogeochemical processes, and further assessed and reviewed island management. Based on $\delta^{15}N$ analyses, it was suggested that soils on an island near the South Island of New Zealand were still controlled by seabird transport and N fixation was limited, even after seabird activity had been suspended for hundreds of years (Hawke et al., 1999). Mizota and Naikatini (2007) found that $\delta^{15}N$ values in soils and plants affected by bird excreta were much higher than in unaffected soils and plants on a volcanic island in the Hatana Islands, Fiji. The authors also reported that ornithogenic soils have higher $\delta^{15}N$ values than soils in other terrestrial ecosystems without birds (~0; Mizota and Naikatini, 2007). Durrett et al. (2014) found that seabird burrow density impacts the spatial heterogeneity of soil and plant properties, including N content and $\delta^{15}N$ values, on New Zealand's offshore islands. Hawke and Condron (2014) found that nutrients (P) in mineral soils from a colony of breeding seabirds gradually become depleted by growing plants, and foliar $\delta^{15}N$ increases consistently with the increasing progressive mobilization of highly recycled forms of N. However, it is important to note that large amounts of guano may cause damage to vegetation due to altered soil nutrient concentrations, pH, and increased physical disturbance (Ellis, 2005). There are also many similar studies that have been conducted on coral islands, largely in the tropics and in areas sensitive to global change (Allaway and Ashford, 1984; Hughes et al., 2003; Miyajima et al., 2016). However, until now there have been few studies of N cycling in the soil–plant systems on coral islands from the perspective of ecosystem evolution (Schmidt et al., 2004; Xu et al., 2011; Honig and Mahoney, 2016) and further study is essential.

The Xisha Islands in the South China Sea are an ideal location to conduct studies of global change in the tropics (e.g., Wu et al., 2017a). Most of the Xisha Islands are formed from coral and therefore provide the opportunity to study N cycling in coral island ecosystems within the same climatic zone. Previous studies have found that seabirds are the first organisms to arrive after the coral islands are formed, where they then transfer large quantities of nutrients in their guano including N and P, enriching the coral sand (Xu et al., 2011, 2016; Wu et al., 2017a). A large number of plants can then colonize the islands. However, to the best of our knowledge, no previous studies related to plant N utilization in this area have been reported. Additionally, there are a small number of plants (both species and individuals) on the islands that receive little or no N input from seabirds (Hainan Ocean Administration, 1999; Tong et al., 2013). Their N sources and utilization strategies are unknown. In this study, we investigated a series of eight coral islands in the Qilian Yu area of the Xisha Islands, South China Sea. These islands varied in density of vegetative cover and three of the islands were unaffected by seabirds. The aim of the study was to test hypotheses on the primary source of N for plants in different island ecosystems. Soils and two dominant plant species were sampled on each island and the N source for soils and plants was determined via $\delta^{15}N$ analyses, as well as nitrate-$\delta^{18}O$ analyses. The influence of seabirds on the growth conditions of plants and changes in the possible N strategy during the development of a coral island ecosystem was also addressed. It was hypothesized that the primary sources of N will vary among islands that are influenced by seabirds and that islands with no or little seabird input receive N primarily from other sources (e.g., N fixation, atmospheric deposition). Thus, we determined if N cycling in the soil–plant system differs on islands affected by seabirds at varying levels, and if the N sources of plants and soils on the islands alter their utilization strategies in accordance with seabird guano input. The results of the study add to the existing knowledge of the evolutionary processes of coral island ecosystems, allow predictions of their fate with global environmental change, and add the understanding and protection of sensitive ecosystems on remote islands.

2. Materials and methods

2.1. Site description

The South China Sea (3°00′–23°37′N, 99°10′–122°10′E), the third largest marginal sea in the world, is located to the south of mainland China and is mostly surrounded by mainland, peninsulas, and islands. The Xisha Islands are a group of about 30 islands, most of which are coral islands that are situated in the northwest of the South China Sea (Fig. 1). The area is located in the central tropics, and has a typical tropical marine climate with a year-round high temperature and an annual average temperature that ranges from 26 to 27 °C, precipitation of 1500 mm, and evaporation capacity of 2400 mm per year. Mature soils on the islands are mainly guano phosphatic coral-sand soils and the remaining immature soils are predominantly composed of coral sand. The central area of some islands is covered by tree species, including *Pisonia grandis* and *Guettarda speciosa*, and shrubs such as *Scaevola taccada*. According to previous reports, >60 species of birds, of which the Red-footed Booby (*Sula sula*) is numerically the most abundant, have been recorded on the islands (Exploration Group of Xisha Islands of Institute of Soil