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How effective are disturbance – tolerant, agroecosystem – nesting ant species in improving soil fertility and crop yield?

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ABSTRACT

Study of the abundance, diversity and nest densities of agroecosystem-inhabiting ant species, in fallow, freshly tilled and cultivated farmers' fields revealed that *Pheidole latinoda* had highest abundance, nest density and disturbance-tolerance ability. Thirty-one arthropod morphospecies belonging to 12 orders were recorded in the nest entrance rim debris piles of this ant species. Hence, *P. latinoda* was selected to study the impact of nest rim debris soil on soil fertility and yield of two common crops, rice and tomato, widely cultivated in the Indo-Gangetic plains of India. Experimental field studies revealed that ant-related enrichment results in significant increase of the C, N and P contents of the bulk soil and a doubling of the soil microbial biomass. The soil enrichment significantly enhanced the yield of both the crop plants in a dose-dependent manner. A significant positive correlation was found between the ecophysiological traits including the specific leaf area, plant height and total plant weight of both rice and tomato plants, and the soil chemical constituents i.e. total C, N, P, NH_4-N, NO_3-N, microbial biomass C, N and P. The ecosystem engineering activities of *P. latinoda* ant colonies apparently enriched the soil via the nutrient cycling activities of the debris arthropods, on the externally discarded organic refuse. Since *P. latinoda* increases productivity via increase in soil fertility and also has the potential to suppress insect pests of crops, conservation of such ant species could enhance agricultural sustainability, through multiple pathways.

1. Introduction

Increase in soil fertility due to the ecosystem engineering activities of a variety of soil- inhabiting organisms has received widespread attention (Jouquet et al., 2006, 2007; Bottinelli et al., 2015) since such activities provide an environmentally friendly link between biodiversity and food security (Chappell and LaValle, 2011), the twin challenges facing the world today. Agronomical practices such as excessive and deep tillage increase yield but only at the cost of loss of carbon and macronutrients (Beniston et al., 2015) while indiscriminate use of chemicals contributes to unsustainable agriculture (Heong et al., 2015; Valiki and Ghanbari, 2015).

Several reports are available which demonstrate the enhancement of soil nutrients by termites (Miyagawa et al., 2011), earthworms (Jouquet et al., 2007; Hume et al., 2015) and ants (Frouz and Jilková, 2008; Shukla et al., 2013). Dung beetles are found to decrease drought stress in crop plants by improving the hydrological properties of soil (Johnson et al., 2015). Thus many soil invertebrates play an important role in nutrient cycling and ecosystem functioning (Jouquet et al., 2006; Jouquet et al., 2014; Schmidt et al., 2015) thereby contributing to ecosystem services (Lavelle et al., 2006). The 4 types of ecosystem services i.e. provisioning, regulating, supporting and cultural, are the benefits people obtain from both natural and human-modified ecosystems (Daily, 1997; Millennium Ecosystem Assessment, 2005). Ants are key contributors of these services in a variety of terrestrial ecosystems since they provide all the 4 categories of ecosystem services (Rastogi, 2011; Del Toro et al., 2012).

Ground-nesting ants increase soil heterogeneity in multiple ways such as by bringing fresh soil from deeper layers to the surface (Cerdà et al., 2009) by increasing the number of macropores (Cerdà and Jurgensen, 2008, 2011) which lead to lower bulk density (Dostál et al., 2005) and also influence the hydrological properties of soil (Cerdà and Doerr, 2010).

Many ant species forage on a wide variety of animal- and plant-based matter which they carry underground, to feed their colony members (Agarwal and Rastogi, 2009; Shukla et al., 2013). The

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unused organic matter is discarded in the refuse piles, which are often located externally at the nest rim (Shukla et al., 2013). The organic matter content and quality of the soil thus enriched is known to affect plant growth (Dean and Yeaton, 1993) as well as its yield (Doan et al., 2015). Ant-induced soil modifications positively affect both plant growth (Wagner and Nicklen, 2010) and below-ground biomass (Dostál et al., 2005). Therefore, further studies need to be focused on their role as ecosystem engineers in providing supporting services by soil modification.

Since rice is the main source of food for nearly half of the world's population, recent attention has been focused on analysis of the ecosystem service providing capacities of rice-dominated landscapes (Burkhard et al., 2015). Rice is the staple cereal crop in India, extensively cultivated in the Indo-Gangetic plains of Uttar Pradesh (U.P.), including Varanasi. Many of the ant-inhabited fields (including the plots which remain fallow during the hot-dry summer season) are later utilized by the farmers for growing this crop. India also happens to be the second largest tomato producer in the world accounting for about 11% of the world tomato production (FAOSTAT, 2012). Tomato cultivation is documented to be the highest in this region (i.e. in Varanasi and Mirzapur), in the state of U.P., in India.

In the rain-fed areas of the Indo-Gangetic plains of India while the wheat crop is grown from November to February i.e. during the cool dry winter season, the rice crop is cultivated after the onset of monsoon i.e. from June-end/July to October, while the fields remain fallow during the hot-dry summer season, extending from March to June (Timsina and Connor, 2001). The conventional practices of growing rice and wheat have resulted in the deterioration of soil physical properties, decrease in water and fertilizer use efficiencies and have lead to stagnation or reduction in grain yields (Zhou et al., 2014). To increase the productivity and sustainability of the cereal production systems, there is, therefore, a need to develop a data base of the key agroecosystem—inhabiting organisms which directly or indirectly contribute to crop plant nutrition. For instance, introduction of frogs in paddy fields suppresses insect pests and also improves the soil nutrients (Teng et al., 2015). Many ant and termite species reduce N decline and enhance wheat crop yield in hot and dry regions (Evans et al., 2011). Also, termite mound soil (Fageria and Baligar, 2004) and earthworm activity reportedly increases rice yield (Choosai et al., 2010).

Several studies have suggested the use of soil amendments to rehabilitate the soil (Zhang et al., 2016) to increase soil water retention capacity (de Melo Carvalho et al., 2014) or to enhance crop plant growth (Mahmoud and Abd El-Kader, 2015). However, soil amendments are time and money expensive while many ecosystem engineering organisms such as ants naturally inhabit agroecosytems. Many ant species abound in tropical crop fields (Choate and Drummond, 2011), such as sponge gourd (Agarwal and Rastogi, 2008) cauliflower (Agarwal et al., 2007) and even in the earthen banks of rice fields (Way and Heong, 2009) where they play a significant role in insect pest suppression (Way et al., 2002). Many ground-nesting ant species tolerant to the disturbance regimes of annual cropping systems play an important role in suppressing/repelling insect pests of crops (Agarwal et al., 2007; Agarwal and Rastogi, 2008). Their role in the soil fertility management of agroecosystems merits study, particularly in view of the recent recognition (Powell and Eisenhauer, 2015) of the importance of soil ecological health. However, direct experimental evidence of the impact of ant colonies on soil fertility is still lacking. We do not have any information on the response of crops to soil nutrients contributed by the nest rim debris piles of agroecosystem-nesting ant species. In an earlier study, we have reported the enhanced concentration of C, N and P in the debris soil of *Pheidole latinoda* Roger, which is characterized by long-lived nests (Shukla et al., 2013).

We hypothesize that the ecosystem engineering activities of common, ground-nesting ant species, in agroecosystems, can influence soil fertility and crop plant productivity. The main objective of the present study therefore, was to examine the effect of the nest debris soil of an ant species with long-lived nests, on soil fertility and crop yield, under experimental field conditions. The best candidate for this would be an ant species which exhibits high nest density and is disturbance tolerant in agroecosystems. Hence, in the first part of this study we investigated the ant diversity, abundance and nest density in fallow and cultivated plots in farmers' fields. We also recorded the time taken for initiation of nest maintenance activities in the fields during the post-tillage period to pin – point the most abundant and disturbance – tolerant ant species in annual cropping systems. Next, we examined the impact of ant nest debris soil on the growth parameters and yield of rice and tomato plants, during experimental field conditions and also the status of the soil nutrients in the debris—amended soil, at the flowering stage of the tomato and rice crop plants.

2. Material and methods

2.1. Study sites and system

There were 2 study sites: farmers' fields and the university botanical garden, both located in Varanasi (25°18′ N latitude and 80°1′ E longitude, 76 m above the mean sea level) in Uttar Pradesh, India. The farmers' fields, used for observation of nest density and diversity of disturbance—tolerant ant species, were located in Madhauli village, (about 10 km distant from the campus). The field experiments were conducted during the Kharif season (July–November 2013), in the Botanical garden of Banaras Hindu University. This area has tropical monsoonal climate. Rice and tomato are the dominant cereal and vegetable crops of this region. The soil of the area is Inceptisol and is silty loam in texture with sand, silt and clay in the ratios of 45%, 29% and 26%, respectively, and is neutral in reaction. The soil has 0.05% total nitrogen and 0.41% organic carbon while its bulk density is 1.35 g/cm^3.

The nests of *Pheidole latinoda* colonies have irregular, crack-like entrance holes (length ranging from 7.86 to 16.4 cm). The debris, characterised by the presence of arthropod carcasses, is typically piled on one side of each nest. The nest rim debris piles have a mean depth of 3.51 ± 0.39 cm (Shukla et al., 2013) and area of 166 ± 13.2 cm^2 (range: 103–231 cm^2). Preliminary studies of excavated plaster of Paris casts of the underground nests of *P. latinoda* suggest that this species constructs deep (~100 cm), vertically oriented nests (Shukla and Rastogi, 2010).

2.2. Ant diversity, abundance, nest density in farmers' fields

The diversity and abundance of agroecosystem-nesting ant species and the nest density of each were recorded in the fallow, tilled and cultivated plots (n = 30 in each case, area of each field = 300 m^2) from March to October 2015. Annual crop plants cultivated in the fields include *Cajanaus cajan*, *Solanum lycopersicum*, *Trifolium alexandrinum*, *Brassica oleracea* and *Oryza sativa*. Pitfall trap sampling method was used for assessment of ant diversity and abundance, in the cultivated fields. The pitfall traps (each of 100 ml capacity, containing 75 ml of ethylene glycol and water in the ratio of 1: 3) were placed, in 7 quadrats/site (15 traps/quadrat; n = 105). Five traps/row (n = 3) were placed, each being 3 m apart from the adjacent one and at least 10 m distant from the nearest ant nest. The traps were retrieved after 24 h and the collected ants were brought to the laboratory for identification. The