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Dinitrogen fixation by the legume cover crop *Pueraria phaseoloides* and transfer of fixed N to *Hevea brasiliensis*—Impact on tree growth and vulnerability to drought

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ABSTRACT

Rubber tree plantations (*Hevea brasiliensis*) are expanding into marginal areas with low soil fertility and long dry seasons with a high risk of soil erosion and drought damage to trees. Introducing an N_2-fixing legume cover crop in rubber plantations may reduce runoff and soil erosion as well as increasing the availability of nutrients but may also increase competition for water. This study quantified the effect of the legume cover crop *Pueraria phaseoloides* on N, P and K nutrition, water status and growth of young rubber trees (three years old in 2007) over a four year period (2007–2010). The plantation was located on a toposequence with a range of soil depths and water storage capacities in northeast Thailand.

The legume aboveground biomass production and its nutrient content and decomposition rate were measured and the N_2 fixation was estimated using the abundance of ^{15}N (δ^{15}N) in the legume. Measurements were taken of the tree stem girth and height and tree leaf predawn water potential, nutrient content and greenness. The transfer of N_2 fixed by the cover crop to the trees was estimated using δ^{15}N in the tree leaves.

The annual biomass production of the legume was 8 Mg ha^{-1} year^{-1} and the N accumulation by the legume was 250 kg N ha^{-1} year^{-1}. The natural abundance method applied to the aboveground components of the legume gave N_2 fixation rates varying from 85 to 93% depending on the year. The leaf δ^{15}N was similar in the three non-legumes (*H. brasiliensis*,*Vetiveria zizanioides* and *Praxelis clematidea*) used as reference plants for estimating the N_2 fixation. The higher level of N and the much lower leaf δ^{15}N values for the rubber trees intercropped with *P. phaseoloides*, compared to rubber trees growing without a legume cover crop, showed that there was a relatively high transfer of fixed N from the legume to the trees, varying from 39% to 46% of tree leaf N depending on the year. Neither N_2 fixation nor N transfer varied significantly along the toposequence. At the bottom of the toposequence, both the nutrient (N, P and K) and water status of trees was significantly improved with the legume cover crop, doubling the tree girth at seven years of age (tree girth: 28 cm, tree height: 700 cm). However, at the top of the toposequence with low water storage capacity, the legume cover crop improved tree nutrition and growth but reduced the trees' ability to survive intense drought.

These results raise concern about the resilience to drought of the rubber tree/*P. phaseoloides* system, since the positive effect of the legume on rubber tree nutrition and growth may increase the risk of water stress and tree mortality. With future changes in climate, an increasing number of areas will be concerned by the question of optimizing the tradeoff between N inputs and water availability.

1. Introduction

Many smallholders in southeast Asia are establishing rubber plantations (*Hevea brasiliensis* Muell. Arg.) in areas with low soil fertility where there is a high risk of soil erosion and nutrient leaching in the rainy season, and drought damage to the trees in the

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long dry season (Watson, 1989). One option to ensure the sustainability of young tree plantations in such conditions may be to plant a perennial N_2-fixing cover crop such as *Pueraria phaseoloides* in the interrows (Broughton, 1977). Although this legume has no direct economic value for farmers, it may provide valuable services such as soil protection against erosion, N_2-fixation and N transfer to the trees, soil carbon sequestration (Cherr et al., 2006; Schroth et al., 2001) and weed control (Bhaskar and Dey, 2010).

The relationship between legume and non-legume species in the nitrogen cycle is generally synergistic with both complementarity and facilitation. The complementarity is largely due to the capacity of legumes to fix atmospheric N_2 through symbiosis with the soil rhizobia unlike the non-legumes. The N_2 fixation by legumes depends on the legume species, the soil and the climatic conditions (Broughton, 1977). In the sandy, acidic soils of northeast Thailand, McDonagh et al. (1995) reported that the quantity of N_2 fixed by *Sesbania rostrata* and *Vigna unguiculata* ranged from 59 to 102 kg ha^{-1} $year^{-1}$ depending on the P and K fertilizers used and the application of lime. Toomsan et al. (1995) reported that the quantities of N_2 fixed by other legumes such as groundnut and soybean cultivated in the same area ranged from 108 to 200 kg ha^{-1} year $^{-1}$.

The facilitation is by the transfer of the N fixed by the legume to the associated non-legume species. N may be transferred by various pathways (Nygren et al., 2012; Peoples et al., 2015). Mineralization of residues is generally the main pathway for N transfer in legume/non legume cropping systems, especially where the aboveground biomass of the legume is recycled to the soil (Ikram et al., 1994; Snoeck et al., 2000; Munroe and Isaac, 2014). However, there is increasing awareness of the contributions by exclusively belowground processes and direct mechanisms of transfer (Sierra and Nygren, 2006; Jalonen et al., 2009; Isaac et al., 2012; Munroe and Isaac, 2014; Nygren and Leblanc, 2015).

The ^{15}N natural abundance method can be used for estimating N_2 fixation by the legume cover crop (Boddey et al., 2000; Unkovich et al., 2008). The percentage of N fixed from the atmosphere (%N_f) is estimated by comparing the $\delta^{15}N$ values in (i) the N_2-fixing plant growing in the field, (ii) a non-N_2-fixing reference plant growing in the same soil, and (iii) the N_2-fixing plant growing in an N-free medium. The reference plant should grow without direct contact with the N_2-fixing plant and is assumed to use the same form of available soil N with the same ^{15}N signature. The use of several reference plants is recommended because often too little is known about the characteristics for selecting a plant that is ecologically and physiologically similar to a given N_2-fixing plant (Boddey et al., 2000; Unkovich et al., 2008; Nygren et al., 2012).

In mixed cropping systems associating a legume and a non-N_2-fixing species, significant modifications to the ^{15}N composition (natural abundance) of the non-N_2-fixing species intercropped with the legume may provide evidence of N transfer between the two species, particularly when confirmed by other measurements of plant and soil N fluxes (Peoples et al., 2015). However, these authors argued that an estimate of N transfer, based on a simple comparison of $\delta^{15}N$ values of non-legumes growing with or without legumes, should be viewed with caution because there may be isotopic fractionation associated with N transformations during transfer.

In a rubber tree plantation intercropped with *P. phaseoloides*, there may be competition between the species, not only for nutrients but also for water and light resources. There may be considerable competition for the soil N pool, particularly when the N_2 fixation and N recycling by the legume cover crop cannot satisfy its own demand for N in subsequent years. Competition for light generally leads to the disappearance of the legume by the time the rubber tree plantation is 7 years old (Broughton, 1977 Watson, 1989). Significant competition for water exerted by *P. phaseoloides* during the immature phase of rubber trees was reported by Delabarre (1998) in experimental sites in Gabon, Ivory Coast and Indonesia on the basis of soil water and tree growth measurements. Unlike these areas, northeast Thailand has a long dry season of about six months with a high vapor pressure deficit and a high risk of waterlogging in the rainy season (Clermont-Dauphin et al., 2013).

This study set out to (i) evaluate the effect on the nutrient and water status and growth of trees of growing *P. phaseoloides* in the interrrows of a young rubber tree plantation in northeast Thailand, (ii) evaluate the N_2 fixation by the legume and transfer of the fixed N to the trees using the ^{15}N natural abundance method, and (iii) evaluate the variability of these results along a gradient of soil depth which induced a soil water storage gradient.

2. Materials and methods

2.1. Site

The site is located in Ban Non Tun, Nong Waeng sub-district, Phra Yuen district, Khon Kaen province, Thailand (16°28′N, 102°45′E). The ecozone is a tropical savanna in the Koppen climate classification (Pidwirny, 2006). The mean annual temperature is 27 °C and the annual rainfall is 1221 mm, 95% of which falls during the well-defined wet season from April to October. There is a pronounced dry season from November to March. During the study period (2007–2010), the highest annual rainfall occurred in 2008 (1957 mm) and the lowest in 2010 (1093 mm). In 2010, the dry season continued until July instead of March (Fig. 1) and the vapor pressure deficit reached 4 kPa (Clermont-Dauphin et al., 2013).

The soil was a superficial, medium-fine loamy sand layer overlying a clayey layer over fractured sandstone. The thickness of the superficial sandy layer increased from 0.60 m at the top to 1.30 m at the bottom of the toposequence (Fig. 2). The average bulk density of the sandy layer was 1.3 Mg m^{-3}. The residual and saturated soil water averaged 0.07 ± 0.04 and 0.37 ± 0.009 m^3 m^{-3}, respectively. The hydraulic conductivity averaged 2 cm h^{-1} (Siltecho et al., 2010). Chemical analysis showed a low pH of 5.51, a low soil organic matter content (SOM) of about 0.45%, and available P and K contents of 3 and 40 ppm respectively.

The thickness of the clayey layer was around 0.10 m at the top, 0.50 m at the middle and 0.70 m at the bottom of the toposequence. The average bulk density of the clayey layer was 1.7 Mg m^{-3}. The residual and saturated soil water contents

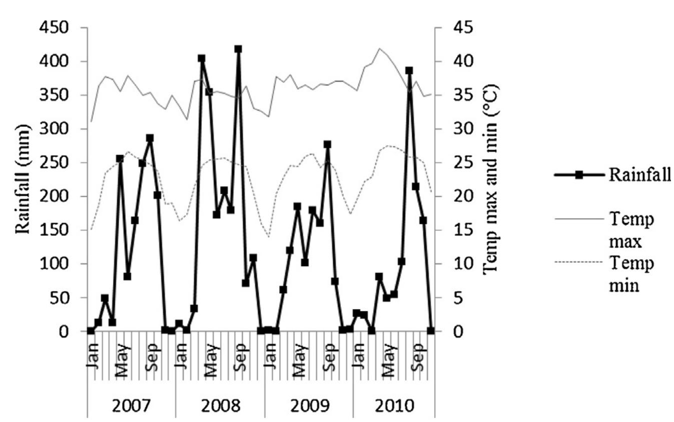

Fig. 1. Rainfall and air temperature in the study area (Ban non tun, Khon Kaen province, Thailand (16°28′N, 102°45′E)).