



Effects of shade-tree species and spacing on soil and leaf nutrient concentrations in cocoa plantations at 8 years after establishment

Shahla Hosseini Bai^{a,*}, Stephen J. Trueman^a, Tio Nevenimo^b, Godfrey Hannet^b, Peter Bapiwai^c, Mathew Poienou^b, Helen M. Wallace^a

^a Centre for Genetics, Ecology and Physiology, University of the Sunshine Coast, Maroochydore DC, QLD 4558, Australia

^b National Agricultural Research Institute, Islands Regional Centre – Keravat, Post Office Box 204, Kokopo, East New Britain Province, Papua New Guinea

^c Papua New Guinea Cocoa Coconut Institute, Kerevat, East New Britain Province, Papua New Guinea

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ABSTRACT

Intercropping in agroforestry systems improves ecosystem services. Appropriate species compositions and spacing regimes are critical to achieve ecosystem benefits and improve yields of all the component crops. Cocoa (*Theobroma cacao*) is an important cash crop globally but it requires shade for survival and growth. However, the effects of shade-tree species composition and spacing regime on nutrient cycling in cocoa plantations are not well understood. This study investigated the effects of shade tree species and spacing regimes on soil and plant nutrient availability at 8 years after plantation establishment in Papua New Guinea. Three cocoa intercropping systems were established in which *T. cacao* was planted with either a non-legume timber tree, *Canarium indicum*, or a legume non-timber tree, *Gliricidia sepium*. The shade-tree spacing regimes included either 8 m × 16 m or 8 m × 8 m in the *Theobroma* + *Canarium* plantations. There was an ongoing thinning regime in the *Theobroma* + *Gliricidia* plantation, with a final shade-tree spacing of 12 m × 12 m. Soil total carbon (TC) and total nitrogen (TN) were significantly higher in the *Theobroma* + *Gliricidia* plantation with 12 m × 12 m spacing and the *Theobroma* + *Canarium* plantation with 8 m × 16 m spacing than in the *Theobroma* + *Canarium* plantation with 8 m × 8 m spacing. Foliar TN and P were correlated with soil TN and P, respectively, whereas no correlation was detected between soil and leaf K concentrations. Foliar TN, P and K were under ideal concentrations for *T. cacao* in all of the plantations. The *Theobroma* + *Gliricidia* plantation had higher soil water extractable phosphorus (P) than the two *Theobroma* + *Canarium* plantations, probably due to frequent pruning of the *G. sepium* trees. Foliar C isotope composition ($\delta^{13}\text{C}$) of *T. cacao* suggested that *T. cacao* close to *G. sepium* or close to *C. indicum* with spacing of 8 m × 16 m and 8 m × 8 m had similar light interception. However, increased *C. indicum* spacing increased the light interception of *T. cacao* trees that were not planted next to *C. indicum*. This study indicated that non-legume timber trees with an optimized spacing regime can be used as overstorey shade trees for *T. cacao*. However, our study indicated all three plantations required fertilisation and better nutrient management.

1. Introduction

Intercropping in agroforestry systems enhances ecosystem services such as biodiversity, nutrient cycling and financial returns to farmers (Jose, 2009; Monroe et al., 2016). Cocoa, *Theobroma cacao* L. (Malvaceae), is one of the most important agricultural crops for export from tropical regions but it is usually intercropped with other trees that provide an overstorey for shade (Donald, 2004; Tschardt et al., 2011). Inter-cropped shade trees in *T. cacao* plantations also increase farm diversity, reduce wind, moderate air temperatures, improve soil nutrient cycling, and increase farm income (Hartemink, 2005; Isaac et al., 2007; Nevenimo et al., 2007; van Beukering et al., 2014).

However, the intercropped tree species and their spacing regime can influence nutrient cycling and the transmission of light to the crop species (Bai et al., 2015a, 2017; Isaac et al., 2007; Vanhove et al., 2016). As a result, it is important to select appropriate tree species for intercropping with *T. cacao* to improve soil nutrient dynamics and minimise competition for light.

Soil organic carbon (C), nitrogen (N), phosphorus (P) and maintenance-metabolism elements including boron (B), calcium (Ca), iron (Fe), potassium (K), magnesium (Mg), manganese (Mn) and zinc (Zn) play an important role in sustaining *T. cacao* growth and yield (Vanhove et al., 2016; Zaia et al., 2012). For example, N is one of the main components of enzymes used in plant photosynthesis (Evans,

* Corresponding author.

E-mail address: shosseini@usc.edu.au (S. Hosseini Bai).

1989) and N isotope composition ($\delta^{15}\text{N}$) of soil samples has been used previously to investigate N transformation in ecosystems (Bai et al., 2015b; Mayor et al., 2014). Increased soil $\delta^{15}\text{N}$ indicates high microbial N transformation and/or N loss from the system (Natalhoffer and Fry, 1988). For example, increased mineralisation and nitrification due to increased organic matter availability, and loss of NO_3^- -N due to leaching, can lead to increased soil $\delta^{15}\text{N}$ (Högberg, 1997; LeDuc et al., 2013) and plant ^{15}N uptake can be translated well into the foliar ^{15}N signal (Högberg, 1997). The maintenance-metabolism elements are also essential for processes in plant leaves, which can be influenced by soil nutrient availability and cycling (Bai et al., 2015c; Ma et al., 2015). *T. cacao* has high demand for N, P and K and so these nutrients are the most likely to be limited in *T. cacao* plantations (Aikpokpodion, 2010; Isaac and Kimaro, 2011). Both shade-tree density and shade-tree species may influence the soil nutrients available for cash crops (Wang et al., 2015) and so appropriate spacing and species are critical to sustain the productivity of *T. cacao* cropping systems.

T. cacao is intercropped with both leguminous and non-leguminous tree species (Nevenimo et al., 2007; Smiley and Kroschel, 2008). The leguminous species biologically fix atmospheric nitrogen (N_2) and increase soil C, N and P pools (Bai et al., 2012; Ma et al., 2015; Tschamtket et al., 2011). *Gliricidia sepium* Jacq. (Fabaceae) is a leguminous shade tree often used in *T. cacao* plantations (Smiley and Kroschel, 2008). However, *G. sepium* is a high-maintenance tree requiring frequent thinning and pruning, which can be a financial burden for farmers, and it is neither a timber tree nor a fruit tree. Thinning of *G. sepium* has also been found to decrease aerial C stocks in a *Theobroma* + *Gliricidia* agroforestry system (Smiley and Kroschel, 2008). Timber, fruit and nut trees have potential as shade trees because they provide additional financial and food security from the intercropping system (Nevenimo et al., 2007; Pauku et al., 2010). It has also been shown that using timber trees such as *Cordia alliodora* (Ruiz & Pav.) Oken, *Tabebuia rosea* (Bertol.) DC. or *Terminalia ivorensis* A. Chev. do not decrease *T. cacao* tree yields, when compared with intercropping with legumes such as *Erythrina poeppigiana* (Walp.) O.F. Cook, *G. sepium* or *Inga edulis* Mart. (Somarrriba and Beer, 2011). *Canarium indicum* L. (Burseraceae) is a valuable timber tree that produces edible nuts, which are consumed by villagers in the southwest Pacific (Randall et al., 2016; Wallace et al., 2016; Walton et al., 2017). *C. indicum* is considered to be an important crop that can increase food security and also be used as a shade tree in *T. cacao* plantations (Nevenimo et al., 2007). However, it is currently unknown how nutrient availability in *T. cacao* plantations is affected by intercropping with *C. indicum* rather than *G. sepium* trees.

The level of overstorey canopy closure and the distance to the nearest shade tree determine light interception in cocoa plantations, often affecting cocoa yield (Koko et al., 2013; van Vliet and Giller 2017). A positive relationship has been found between light interception and yield in *T. cacao*, and planting shade trees closer than 10 m to *T. cacao* trees can decrease cocoa pod production significantly (Koko et al., 2013). Therefore, it is important to assess the effects of alternative shade trees on light interception by cocoa. Foliar C isotope composition ($\delta^{13}\text{C}$) is a reliable variable to explore light interception, as influenced by shade trees, and which also associates with plant water stress and photosynthesis (Bai et al., 2013; Duursma and Marshall, 2006; Ma et al., 2015). Plants discriminate against heavier C isotopes and preferentially fix $^{12}\text{CO}_2$ rather than $^{13}\text{CO}_2$ at the carboxylation site in the leaf when there is no C limitation for photosynthesis (Farquhar and Richards, 1984). Sun-exposed leaves have higher $\delta^{13}\text{C}$ values (the ratio of the stable isotopes, $^{13}\text{C}:^{12}\text{C}$) due to longer periods of stomatal closure when compared with shaded leaves (Duursma and Marshall, 2006). Although leaves with increased shading may have higher $^{12}\text{CO}_2$, it is possible that N becomes a limiting factor in shaded leaves due to shifts in N allocation, leading to decreased foliar N in shaded trees compared with sun-exposed leaves (Kranabetter et al., 2010).

Our objective was to explore the effects of two shade-tree species, *G. sepium* and *C. indicum*, and tree spacing on soil and foliar nutrient

concentrations of *T. cacao*. We studied three 8-year-old plantations where *G. sepium* had 12 m \times 12 m spacing and *C. indicum* had 8 m \times 8 m or 8 m \times 16 m spacing regimes. We hypothesized that *C. indicum* at 8 m \times 8 m spacing decreases soil and leaf nutrient concentrations in *T. cacao* due to increased nutrient uptake from the plantation soil. We also hypothesized that *G. sepium* increases soil nutrient concentrations more so than *C. indicum*.

2. Methods and materials

2.1. Site description and experimental design

The experimental plantations were located at Keravat (4°21'S 152°2'E), East New Britain, Papua New Guinea (PNG). Keravat is categorised as tropical with average annual temperature of 27 °C and 2600 mm annual precipitation (Climate-Data.org: <http://en.climate-data.org/region/1958/>).

One *Theobroma* + *Gliricidia* plantation and two *Theobroma* + *Canarium* plantations were established in 2007. The three plantations were approximately 100 m apart. In the two *Theobroma* + *Canarium* plantations, the *C. indicum* spacings were 8 m \times 16 m and 8 m \times 8 m (78 trees ha⁻¹ and 156 trees ha⁻¹, respectively) (Fig. 1a). The *T. cacao* trees had been planted with a spacing of 4 m \times 4 m and 4 m \times 2 m in the *Theobroma* + *Canarium* plantations with *C. indicum* spacing of 8 m \times 16 m and 8 m \times 8 m, respectively (Fig. 1a and b). In the *Theobroma* + *Gliricidia* plantation, the *G. sepium* spacing was 4 m \times 4 m at the establishment phase with one *G. sepium* planted in the centre of four cocoa trees (Fig. 1c). Thinning of *G. sepium* commenced at 3 years after establishment and continued for 4 years until a final spacing of 12 m \times 12 m (69 trees ha⁻¹) was achieved. The *T. cacao* trees had been planted with a spacing of 4 m \times 4 m in this plantation. *G. sepium* was usually pruned quarterly, whereas *C. indicum* trees were never pruned. Two major prunings took place annually for the *T. cacao* trees in all plantations. No fertiliser was applied in any of the plantations.

Three replicated plots of 25 m \times 25 m each were established in different parts of each plantation in October 2015. In the *Theobroma* + *Canarium* plantations, two transects (25 m long, West-East; Fig. 1a and b) were marked in the middle of each plot, one transect between the *T. cacao* and *C. indicum* planting rows (named as cacao-*Canarium*) and one transect between the *T. cacao* and *T. cacao* planting rows (named as cacao-cacao) (Fig. 1a and b and Table 1). In the *Theobroma* + *Gliricidia* plantation, all *T. cacao* trees had initially been planted adjacent to one *G. sepium* (see Fig. 1c) and, despite some of the *G. sepium* trees having been thinned, their trunks and residues remained on the ground. As a consequence, a real cacao-cacao transect did not exist in the *Theobroma* + *Gliricidia* plantation. Hence, we established one transect in the middle of each plot where *G. sepium* still existed next to *T. cacao* planting rows (Fig. 1c). The sampling transect in the *Theobroma* + *Gliricidia* plantation was named cacao-*Gliricidia* (Fig. 1c, Table 1).

2.2. Soil sample collection and chemical analysis

Five soil samples were collected at 5 m intervals along each 25 m long transect, at 5 m, 10 m, 15 m, 20 m and 25 m (Fig. 1d) in October 2015 from a depth of 0–10 cm using an auger (60 mm internal diameter). To measure soil nutrient concentrations, top soil is the most important layer because soil microbial biomass, which breaks down organic matter to available nutrient, decreases significantly with increasing soil depth (Aponte et al., 2013; Bai et al., 2015a). At each sampling point, the three soil samples were collected on the transect and 0.5 m perpendicularly on each side of the transect (Fig. 1d). These three soil samples at each point were bulked to create one sample per sampling point (Fig. 1d), generating five soil samples for each transect. Soil samples were placed in clip-locked plastic bags and transferred to

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