Plant Phosphorus Uptake in a Soybean-Citrus Intercropping System in the Red Soil Hilly Region of South China*1

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(Received April 18, 2008; revised December 15, 2008)

ABSTRACT

A field microplot experiment was conducted in the red soil hilly region of South China to evaluate plant phosphorus (P) uptake under soybean and citrus monoculture and the soybean-citrus intercropping system using the 32P tracer technique. P fertilizer was applied at three depths (15, 35, and 55 cm). The experimental results showed that the planting pattern and 32P application depth significantly affected the characteristics of P uptake by soybean and citrus. Under the soybean-citrus intercropping system, considerable competition was observed when the 32P fertilizer was applied to the topsoil (15 cm); therefore, the 32P recovery rate declined by 41.5% and 14.7% for soybean and citrus, and 32P supplying amount of topsoil to soybean and citrus decreased by 346.8 and 148.1 mg plot−1, respectively, compared to those under the monoculture. However, 32P recovery of soybean was promoted when 32P fertilizer was applied to the deeper soil layers (35 and 55 cm) under soybean-citrus intercropping. Under the soybean monoculture, 32P fertilizer could hardly be used by soybean when 32P fertilizer was applied at the 55 cm depth or below, with the recovery rate being less than 0.1%; it was up to 0.253% by soybean under intercropping. The higher P recovery of soybean under soybean-citrus intercropping when P was applied in the deeper soil layers was because part of the P nutrient that the citrus absorbed from the deeper soil layers could be released into the topsoil and then it could be used by the soybean.

Key Words: citrus, intercropping, monoculture, P uptake, soybean


INTRODUCTION

Light, heat, water, and nutrient resources could be fully used by crops and trees and water and soil losses and fertility reduction could be efficiently prevented under reasonable intercropping (Vandermer, 1989; Ruan and Zhou, 1995; Yuan et al., 1999). The main interspecific relationships are facilitation and competition and they exist together in the intercropping system. When competition is higher than facilitation, the disadvantage of intercropping is significant; when competition is lower than facilitation, advantage of intercropping is of importance (Vandermer, 1989). Before the 1980s, light and heat competition of plant aboveground parts have been studied and many useful results have been obtained (Vandermer, 1989; Zhang et al., 1998; Ong et al., 2000). In the recent decade, the studies on water and nutrient competition and facilitation of plant underground parts have become a bigger concern; therefore nitrogen (N) and phosphorus (P) competition in intercropping annual crops has been evaluated by several investigators using the 15N and 32P trace technique (De Rajat et al., 1984; Caldwell et al., 1985; Ashokan et al., 1988; George et al., 1996; Akinfesi et al., 1997; Ong et al., 2000). However, there are very limited data on integrated tree-crop system. The agroforestry system is a very popular pattern used on dry land and slope soils in the red soil hilly region of South China. With low P content

*1Project supported by the Knowledge Innovation Program of the Chinese Academy of Sciences (No.KZCX2-407) and the Knowledge Innovation Program of Hunan Agricultural University (No.04YJ10).
and low utilization rate of P fertilizer in the red soil region of China (Lu et al., 2000), competition for native soil P and chemical fertilizer P among component plants is an important factor that limits productivity of the agroforestry systems (Nair, 1984). Although many of these systems rely heavily on the exploitation of component interactions, information of the underlying mechanisms is often limited according to Nair (1993). Among the negative (production-decreasing) interactions common to these systems, competition for light, water, and nutrients is perhaps the most important. Planting pattern and fertilizer application methods are the key factors in determining the nature and magnitude of interspecific competition (underground) in a mixed species system.

Citrus is the main fruit planted in the red soil hilly region of southern China and the benefits of P fertilizer to citrus have been analyzed (Shen, 1990). Soybean is an important economic and oilseed crop in this region as well. The amount of nodulation and yield of soybean increase after P fertilizer application (Ding and Li, 1998). Soybean-citrus intercropping is an important planting pattern in dry land and slope soil of red soil region of South China. This intercropping system can increase the soil fertility because of nitrogen fixation of soybean and the utilization of water and nutrients in the deeper soil layers by the extensive root system of citrus. However, few studies have been done on the mechanism of nutrient absorption and transferring under this pattern. This study aimed at evaluating and comparing the characteristics of phosphorus uptake by soybean and citrus under monoculture and the soybean-citrus intercropping system when P fertilizer was applied at different soil depths.

MATERIALS AND METHODS

The experiment was conducted at the Taoyuan Experimental Station of Agroecosystem Research, Chinese Academy of Sciences (28° 55′ N, 111° 33′ W), in April 2001. Annual average rainfall and temperature were 1 447.9 mm and 16.5°C, respectively. The soil (0–15 cm) at the experimental site is an acidic Oxisol with pH (water) 4.54, organic matter 21.8 g kg$^{-1}$, total P 0.66 g kg$^{-1}$, total K 13.9 g kg$^{-1}$, alkaline solution N 113.6 g kg$^{-1}$, Olsen P 6.8 g kg$^{-1}$, and neutral NH$_4$OAC exchangeable K 53.7 g kg$^{-1}$.

The experimental design was a randomized complete block with three replications. Nine treatments included three planting patterns (soybean-citrus intercropping, soybean monoculture, and citrus monoculture) by three $^{32}$P fertilizer application depths (15, 35, and 55 cm). The citrus trees were planted with a spacing of 300 cm × 300 cm in winter 1995. Soybean (Tiefeng No. 29) was seeded at a spacing of 35 cm × 30 cm on April 15, 2001. For citrus-soybean intercropping, the radius of each microplot was 150 cm. In each microplot, soybean was planted in four circles with a citrus tree in the center, with the radii being 45, 80, 115, and 150 cm, and 8, 16, 24, and 32 pits of soybean, totaling 80 pits, being planted from the first to the fourth circle, respectively. Under citrus monoculture, soybean was not planted and the layout for the respective treatments was the same. Details of the planting patterns are diagrammed in Zhou et al. (2006).

On the day prior to soybean seeding, 100 g N as urea and 28.2 g K as KCl were applied to the topsoil (0–15 cm) in all the plots. After one month, $^{32}$P was applied to depths at 20-cm intervals (up to 80 cm) using a soil borer at distances of 27.5, 62.5, and 97.5 cm from the center of the plots. Sixty equally spaced holes were dug to the required depths in each microplot, with 8, 20, and 32 holes on each circle (Zhou et al., 2006). A polyvinyl chloride (PVC) (1 cm in diameter) access tube was inserted into each hole and 20 mL $^{32}$P solution in potassium dihydrogen phosphate carrier (36.3 mg P L$^{-1}$) was dispensed into the tube on May 15, 2001 (at the fourth leaf stage of soybean) using a pipette. After dispensing the P solution, any labeled solution adhering to the inner walls of the tube was washed down with a jet of about 10 mL water. The total radioactivity applied to 15, 35, and 55 cm soil depths was 5.0 × 10$^{8}$, 7.4 × 10$^{8}$, and 10.5 × 10$^{8}$ Bq, respectively.

Each microplot was divided into two parts and plant and soil samples were taken from each part on the forty-fifth day after $^{32}$P application (June 25, 2001, at soybean pod-setting stage). Leaf, stalk, legume, and root samples of soybean were harvested and washed with distilled water and dried at 80 °C.
in an oven and weighed, individually. After the aboveground parts of citrus was cut, new leaf (germinated in the same year), old leaf (germinated previously), the first branch (main stock), the second and third branch, and new branch (germinated in the same year) samples were separated, the xylem and phloem of the first and second branches were peeled off, and then they were washed with distilled water and dried at 80 °C before weighing. Sub-samples were taken for determination of total P content and radioactivity. Soil samples within 0–25, 25–100, and 100–125 cm from the center of the plots were taken at four depths (0–20, 20–40, 40–60, and 60–80 cm), placed on plastic boards, and then homogenized by hand so that plant roots were evenly distributed. Soil sub-samples were collected for the determination of total P content and radioactivity. Before soil samples were collected, their bulk density and water content were determined using a metal cylinder. Total P content of plant and soil samples was determined using wet digestion (H$_2$SO$_4$ and HClO$_4$) and colorimetric assay. $^{32}$P radioactivity of $^{32}$P fertilizer, and plant and soil samples was determined using an FH408 counting technique with an FJ-367 scintillation system.

The recovery rate of $^{32}$P fertilizer (%), the supplying amount of $^{32}$P fertilizer to plant (g plot$^{-1}$), the supplying ratio of P fertilizer to plant, and total P absorption amount by plant (g plot$^{-1}$) were calculated as follows: the recovery rate of $^{32}$P fertilizer = $^{32}$P total radioactivity in plant × 100/$^{32}$P total radioactivity in fertilizer; the supplying amount of $^{32}$P fertilizer to plant = P fertilizer amount (g plot$^{-1}$) × the recovery rate of $^{32}$P fertilizer (%); the total P absorption amount by plant = dry matter of plant (g plot$^{-1}$) × P content of plant (g kg$^{-1}$); and the supplying ratio of P fertilizer to plant = the supplying amount of $^{32}$P fertilizer to plant × 100/the total P absorption amount by plant. All calculations were carried out using Excel 2000. All statistical analyses were carried out using SAS 6.12 software (SAS Institute Inc., Cary, USA). Data were subjected to analyses of variances to evaluate difference among the treatments and least significant difference (LSD) test at the 5% probability level was used to compare treatment means.

RESULTS

Total cumulative amount of P in plants

The planting pattern and the P application depth significantly affected total cumulative amount of P in soybean (Table I). The total cumulative amount of P in soybean was remarkably greater under soybean monoculture than under soybean-citrus intercropping. Under soybean monoculture, the total cumulative amount of P in soybean was the highest when P was applied in the topsoil (15 cm soil layer), and it was much higher than that under the other two depths of P applications (35 and 55 cm). However, considerable difference in the total cumulative amount of P in soybean was not observed when P was applied at 35 or 55 cm. On the other hand, under soybean-citrus intercropping, P application depth did not affect the total cumulative amount of P in soybean.

### TABLE I

Total cumulative amount of phosphorus in soybean and citrus with $^{32}$P applied at different soil depths (15, 35, and 55 cm)

<table>
<thead>
<tr>
<th>Plant</th>
<th>Soybean monoculture</th>
<th>Soybean-citrus intercropping</th>
<th>Citrus monoculture</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15 cm</td>
<td>35 cm</td>
<td>55 cm</td>
</tr>
<tr>
<td>Soybean</td>
<td>6.84a)</td>
<td>6.39b</td>
<td>6.18b</td>
</tr>
<tr>
<td>Citrus</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^{a)}$Values followed by the same letter are not significantly different at the 5% level.

Under citrus monoculture, total cumulative amount of P in citrus was not affected when P was applied in the topsoil and 35 cm soil layer, whereas it was significantly decreased with P application at
55 cm soil layer. But under soybean-citrus intercropping, the total cumulative amount of P in citrus decreased with increased depth of P fertilizer application.

$^{32}$P recovery

Data of $^{32}$P recovery by soybean and citrus are given in Table II. Considerable differences were observed for $^{32}$P recovery by soybean and citrus among planting patterns. After $^{32}$P fertilizer was applied in the topsoil (15 cm), $^{32}$P recovery by soybean was 41.5% less in soybean-citrus intercropping than in soybean monoculture, whereas $^{32}$P recovery by citrus was 14.7% less in soybean-citrus intercropping than in citrus monoculture. $^{32}$P recovery was 104.8% and 66.0% higher by soybean than by citrus under monoculture and intercropping, respectively. However, the sum of $^{32}$P recovery by both soybean and citrus was 13.3% and 1.3 times higher under intercropping than under soybean monoculture and citrus monoculture, respectively, when $^{32}$P was applied in the topsoil.

| TABLE II |

<table>
<thead>
<tr>
<th>Plant</th>
<th>$^{32}$P recovery rate by soybean and citrus with $^{32}$P applied at different soil depths (15, 35, and 55 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Soybean monoculture</td>
</tr>
<tr>
<td></td>
<td>15 cm</td>
</tr>
<tr>
<td>Soybean</td>
<td>5.421a</td>
</tr>
<tr>
<td>Citrus</td>
<td>2.308b</td>
</tr>
<tr>
<td>Total</td>
<td>5.421b</td>
</tr>
</tbody>
</table>

a) Values followed by the same letter are not significantly different at the 5% level.

Under intercropping, $^{32}$P recovery of soybean increased by 32.2% and that of citrus decreased by 12.8% compared to those in monoculture when $^{32}$P fertilizer was applied in the 35 cm soil layer. $^{32}$P recovery was 20.3% less by soybean than by citrus under monoculture, whereas it was 20.8% higher by soybean than by citrus under intercropping when $^{32}$P was applied in the 35 cm soil layer. Similarly, when $^{32}$P was applied in the 35 cm soil layer, the sum of the $^{32}$P recovery by soybean and citrus was observably promoted under soybean-citrus intercropping, 141.6% and 92.5% higher than under soybean monoculture and citrus monoculture, respectively.

Under soybean monoculture, soybean could hardly use the $^{32}$P fertilizer that was applied 55 cm or below, and $^{32}$P recovery was only 0.092%. But under soybean-citrus intercropping, $^{32}$P recovery of soybean was significantly increased, up to 0.253%. On the other hand, $^{32}$P recovery of citrus was much higher under monoculture than under intercropping with $^{32}$P applied at 55 cm soil layer. No considerable difference of $^{32}$P recovery was observed between monoculture and intercropping.

Contribution rate of $^{32}$P fertilizer

The advantage of $^{32}$P trace technique was that it was able to distinguish whether the cumulative amount of P in plants was coming from the fertilizer or the native soil. The P amount from the fertilizer was considered as the supplying amount of fertilizer and the percentage of the P amount from fertilizer to total cumulative amount of P in plants was considered as the contribution rate of fertilizer. The experimental results showed that both $^{32}$P supplying amount and $^{32}$P contribution rate to soybean decreased with increased depth of $^{32}$P application (Fig. 1). $^{32}$P contribution rate to soybean increased under intercropping with P fertilizer applied at both topsoil and deep soil layers. However, $^{32}$P supplying amount was significantly different between $^{32}$P application depths, larger for the topsoil application and smaller for the deep soil layer application under soybean monoculture than under intercropping.

$^{32}$P supplying amount to citrus decreased with increased P fertilizer application depth and was remarkably decreased under soybean-citrus intercropping compared with citrus monoculture (Fig. 2). $^{32}$P contribution rate revealed difference between $^{32}$P application depths. When P fertilizer was applied
Fig. 1  $^{32}$P supplying amount and $^{32}$P contribution rate to soybean. S15, S35, and S55 are the treatments of soybean monoculture with $^{32}$P applied at soil depths of 15, 35, and 55 cm, respectively. SC15, SC35, and SC55 are the treatments of soybean-citrus intercropping with $^{32}$P applied at soil depths of 15, 35, and 55 cm, respectively.

Fig. 2  $^{32}$P supplying amount and $^{32}$P contribution rate to citrus. C15, C35, and C55 are the treatments of citrus monoculture with $^{32}$P applied at soil depths of 15, 35, and 55 cm, respectively. SC15, SC35, and SC55 are the treatments of soybean-citrus intercropping with $^{32}$P applied at soil depths of 15, 35, and 55 cm, respectively.

in the topsoil and 55cm soil layer, $^{32}$P contribution rate was higher under monoculture than under intercropping, but in contrast, $^{32}$P contribution rate was lower under monoculture than under intercropping with P fertilizer application in 35 cm soil layer.

**Root biomass distribution**

The data in Table III showed that soybean root biomass decreased with soil depth. About 70% soybean roots were found in the 0–20 cm soil layer and about 30% in the 20–40 cm soil layer. Soybean root distribution was affected by the planting pattern and application depth of P fertilizer. Soybean root biomass was much higher under monoculture than under intercropping and was remarkably decreased with increased P application depth under both monoculture and intercropping. The percentage of root biomass in the 0–20 cm soil layer to the total root biomass was greater and that of the 20–40 cm soil layer was lower under monoculture than under intercropping. Obviously, P fertilizer was the important factor that stimulated the soybean roots to spread to deeper soil layers.

**TABLE III**

Root biomass distribution of soybean in the soil profile (0–40 cm) with $^{32}$P applied at different soil depths (15, 35, and 55 cm)

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Root biomass</th>
<th>Monoculture</th>
<th>Intercropping</th>
<th>LSD$_{0.05}^{a}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount (g plot$^{-1}$)</td>
<td>15 cm</td>
<td>35 cm</td>
<td>55 cm</td>
</tr>
<tr>
<td>0–20</td>
<td>155.4</td>
<td>145.1</td>
<td>140.9</td>
<td>130.0</td>
</tr>
<tr>
<td></td>
<td>Percentage (%)</td>
<td>73.4</td>
<td>71.2</td>
<td>70.5</td>
</tr>
<tr>
<td>20–40</td>
<td>56.2</td>
<td>58.6</td>
<td>58.9</td>
<td>48.3</td>
</tr>
<tr>
<td></td>
<td>Percentage (%)</td>
<td>26.6</td>
<td>28.8</td>
<td>29.5</td>
</tr>
</tbody>
</table>

$^{a}$Least significant difference at the 5% probability level.

Citrus root system had formed when the experiment was conducted because citrus was planted six years ago. Citrus root biomass was not influenced either by planting pattern or P application depth. More than 58% of the root biomass was found in the 0–20 cm soil layer, whereas less than 3% root biomass was found within the 60–80 cm soil layer (Table IV).
TABLE IV

Root biomass distribution of citrus in the soil profile

<table>
<thead>
<tr>
<th>Soil layer</th>
<th>Coarse roots (diameter &gt; 2 mm)</th>
<th>Fine roots (diameter &lt; 2 mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Amount (g plot⁻¹)</td>
<td>Percentage (%)</td>
</tr>
<tr>
<td>cm</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0–20</td>
<td>190.2</td>
<td>33.7</td>
</tr>
<tr>
<td>20–40</td>
<td>65.2</td>
<td>11.6</td>
</tr>
<tr>
<td>40–60</td>
<td>61.9</td>
<td>11.0</td>
</tr>
<tr>
<td>60–80</td>
<td>15.4</td>
<td>2.7</td>
</tr>
</tbody>
</table>

DISCUSSION

Chen (1962) reported that $^{32}$P recovery rate by soybean was 0.7%–6% when $^{32}$P was applied below 30 cm soil layer. Suman et al. (1996) reported that $^{32}$P recovery by shrub decreased with increasing P application depth and lateral distance. The results of this investigation showed that the $^{32}$P recovery declined rapidly with increasing P application depth and was less than 1% when P was applied at 55 cm soil layer under both monoculture and intercropping. When $^{32}$P fertilizer was applied in 55 cm soil layer, it could hardly be utilized by soybean under soybean monoculture, and $^{32}$P recovery rate was less than 0.1%. It was possibly because the P diffusion coefficient was much smaller in soil (Dong, 1995), and P absorption by the plant depended mainly on root contact with P fertilizer. On the other hand, the results in Tables III and IV showed that about 70% roots of soybean existed in the 0–20 cm soil layer, and about 80% fine roots of citrus were concentrated in the 0–40 cm soil layer.

$^{32}$P recovery was much higher in both crop and wood under the agroforestry system rather than under monoculture (George et al., 1996; Yuan et al., 1999). In this study, under soybean-citrus intercropping with P application at 15, 35, and 55 cm soil layers, $^{32}$P recovery increased by 13.3%, 141.6%, and 931.5% and 132.0%, 92.5%, and 5.4% compared to that under soybean and citrus monoculture, respectively. Obviously, soybean-citrus intercropping could increase $^{32}$P recovery.

When P was applied in the topsoil in intercropping, $^{32}$P recovery and total cumulative amount of P in soybean were remarkably decreased, but $^{32}$P contribution rate increased by 5.1% compared to soybean monoculture; however, no considerable difference of total cumulative amount of P in citrus was observed, $^{32}$P recovery of citrus declined remarkably up to 14.7%, and $^{32}$P contribution rate decreased by 10.9%. These results indicated that soybean-citrus intercropping was characterized by the distinct competition when P was applied in the topsoil. Similar results were obtained from woods-grass intercropping system and crop-fruit intercropping by Ashokan et al. (1988) and George et al. (1996).

Under intercropping, $^{32}$P recovery rate was higher by soybean when P was applied in the topsoil. In contrast, $^{32}$P recovery rate was higher by citrus when P was applied in the deeper soil layer (55 cm). This was because the $^{32}$P fertilizer was applied between two rows of soybean and the large amount of root biomass of soybean in the 0–20 cm soil layer (Table III) favored absorption of the $^{32}$P fertilizer. Although about 55% citrus roots were found in the 0–20 cm soil layer (Table IV), the density of fine roots was less than that of soybean, so $^{32}$P recovery rate was lower. Secondly, plant nitrogen fixation relied more heavily on P fertilizer so competition for P was higher in soybean. On the other hand, diffusion coefficient of P in soil was very small and soil bioavailable P was determined by the biological characteristics of plant roots (root length, root diameter, root surface area, root structure, and root secretion) to a large extent (Gardner et al., 1983; Ae et al., 1990). The roots of citrus could reach into the deeper soil layer with about 20% of the roots in the 20–40 cm soil layer and about 15% of the roots in 40–60 cm, indicating that citrus favored absorption of P from the deep soil layer.

Interestingly, $^{32}$P recovery rate of soybean was significantly greater under intercropping than under monoculture when P was applied at deeper soil layers. For example, $^{32}$P recovery rate was 32.2% and
175% higher than that in soybean monoculture when P was applied in the 35 and 55 cm soil layers, respectively. Although $^{32}$P recovery rate was only 0.2%, $^{32}$P could hardly be utilized by soybean under monoculture because $^{32}$P recovery rate was less than 0.1% when P was applied in the 55 cm soil layer. This result suggested that the crop-tree system could promote shallow root crops to absorb and utilize P in deeper soil layers. The reason might be very complicated, but the hypotheses could be established: under agroforestry system, deep root woody plants absorbed nutrients from deep soil layers and these nutrients were then transported to tissue organs. A part of those nutrients could be released into the topsoil via physiological metabolism, for example, root secretion or root hair breaking, root cell dying, and falling off. These released nutrients could be absorbed by the shallow root crop. On the other hand, the nutrients released when litter of woody plants decomposed could also be utilized by the shallow root crop. Under the mixed planting system, the phenomenon that nutrients were transferred from one plant to other plants was reported (Chiariello et al., 1982; Caldwell et al., 1985). Of course, the recovery rate of nutrients in deeper soil layers by shallow root crops was limited by the nutrient supplying capacity of the woody plant, which was related to the competition capacity of that crop for absorbing nutrients in rhizosphere. Therefore, further study should focus on the mechanism of nutrient release, absorption, and competition in crop-tree systems.

REFERENCES


