Nutr Cycl Agroecosyst (2008) 81:71–83
DOI 10.1007/s10705-007-9153-z

RESEARCH ARTICLE

Nitrogen competition in contour hedgerow systems in subtropical China

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Received: 26 March 2007 / Accepted: 10 October 2007 / Published online: 17 November 2007

Abstract Contour hedgerow agroforestry has been studied for soil erosion control and soil fertility improvement in subtropical China. However, below-ground competitive and complementary interactions between tree hedges and crops have received relatively little attention in the scientific literature. A field experiment was conducted to explore the effects of a leguminous shrub hedge, false indigo (*Amorpha fruticosa*) and a non-legume gramineous hedge, vetiver (*Vetiveria zizanioides*), on the growth of soybean (*Glycine max*). Pot experiments were also carried out to determine the effect of below-ground interactions on nitrogen uptake between two contour hedgerow agroforestry with a ^{15}N isotope method and root partition, i.e., a sheet barrier, a mesh barrier and no barrier. The results showed that the relative disadvantage of intercropping, expressed as land equivalent ratio, were 0.96/0.97 for the *A. fruticosa*–soybean system and 0.99 for the vetiver–soybean system, based on the dry matter (DM) production and N acquisition. Both area-adjusted yield and N content of soybean were significantly decreased in two intercropping treatments compared to those in the sole soybean treatment. The DM production of soybean, for example, was decreased by 10% and 5% under *A. fruticosa* and vetiver, respectively, when compared to the sole soybean. The intercropping disadvantage was mainly due to interspecific competitive interaction. The result was proved by lower yields and biomasses adjacent to the hedgerows. The ^{15}N-based estimates of N uptake, in the vetiver–soybean system, of soybean with mesh separation (6.11 mg pot^{-1}) was lower than that (13.85 mg pot^{-1}) with no root separation, for vetiver the higher ^{15}N uptake was observed in no root separation (13.90 mg pot^{-1}). In the *A. fruticosa*–soybean system, the lower ^{15}N uptake of soybean (1.53 mg pot^{-1}) and *A. fruticosa* (6.42 mg pot^{-1}) were observed in no root separation. It is concluded that the growth of soybean was unexpectedly suppressed in two intercropping systems. The growth of *A. fruticosa* was clearly suppressed due to below-ground interactions, yet the growth of vetiver was improved to a great extent.

Keywords Hedgerow · Interaction · Intercropping · N uptake · Root partition · Soybean

Introduction

Hilly purple soil, one of the important soils for agricultural production in subtropical areas of China,

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is very common in the upper reaches of the Yangtze River. Because of abundant rainfall and topographic conditions, high soil loss occurs during intense storms (Shi et al. 2004). Moreover, intensive cultivation and socioeconomic pressure have accelerated the rate of soil erosion on sloping land (Du 1994). As a result, soil erosion is a serious hindrance to agricultural development in this area.

Growing tree hedge species established along contours, such as indigo bush (*Amorpha fruticosa* L.), vetiver (*Vetiveria zizanioides* (L.) Nash) and white leadtree (*Leucaena leucocephala* Lam de Wit), in subtropical China has been recommended as a strategy to prevent soil from erosion on sloping lands (Sun et al. 2004). In recent years, several reports have documented that contour hedgerow agroforestry can improve soil fertility and increase crop yields (Zhang et al. 2001; Hellin and Haigh 2002; Xu et al. 2002). On the other hand, hedges intercrops could capture part of the resources (i.e., nutrients, water and light) which would otherwise be available to the crops intercrops (Sanchez 1995; Ong et al. 1996; Friday and Fownes 2002). This could decrease the production of crops or the whole system. Hence, the primary objective of this study was to compare the productivity and sustainability of applying tree hedges in the specific ecosystem.

In some cases, below-ground interactions in agroforestry define productivity and sustainability, both complementary and competitive (Lehmann et al. 1998). Knowledge of specific mechanism of below-ground interactions would help managers to develop optimum management strategies to improve soil sustainability and crop productivity. However, the below-ground interactive effects on nutrient uptake between tree hedges and crops are difficult to determine due to their complex geometries. It has been hypothesized that assessment of the root distribution may give valuable information about the architecture of the below-ground biomass, but often fails to quantify short-term dynamics of nutrient uptake (Dinkelmeyer et al. 2003). Thus, more understanding is needed of the below-ground interactive dynamics of nutrient in hedge–crop systems. Wu et al. (1985) pointed out that the interactive effects would be more visible if resource distribution is refined by means of spatial partition. A novel method involving partitioning roots either by solid barrier and mesh barrier can be convenient to study the interspecific competition and facilitation effects in intercropping system (Xiao et al. 2004). In some studies reported, root barriers were effective in reducing or eliminating below-ground competition compared with the non-barrier treatments (Singh et al. 1989; Jose et al. 2000; Samuel et al. 2004). For the present experiment, it was hypothesized that crop biomasses and yields would be increased dramatically by means of barriers in the soil between the hedgerows and the crops. However, separate assessment of nutrient uptake by individual plants solely in intercropping systems is impossible without tracer techniques (Lehmann and Muraoka 2001). Hence, we used root partition combined with ^{15}N isotope labeled method to compare competition for N between hedgerows and soybean. A second objective of this study was: (i) to determine the competition between hedgerows and soybean can change the relative N uptake by soybean, and (ii) to quantify the recovery of fertilizer N in plants with and without root contact.

Materials and methods

Site description

The field experiment was performed at Zigui, Hubei province, China (31°12′N, 110°42′E, about 240 m asl) during the 2003 growing season. The experiment site is about 50 km northwest of the Three-Gorge Dam. Natural resources and land use patterns in the study area are typical of subtropical China. The arable land is primary sloped or terraced, and the soil is classified as Ultisols, based on the soil Taxonomy of the U.S.D.A. (Soil Survey Staff 1999). The region is in a subtropical monsoon climate zone; the mean annual temperature is 16.7°C, with an average summer high of 28°C in July and an average winter low of 8°C in January. The rainfall distribution is unimodal with maximum between May and September (70% of annual rainfall) and a mean annual rainfall is about 1,016 mm. Rainfall was 434 mm between 1 June and 30 September 2003. The major agricultural crops are wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.), soybean (*Glycine max* (L.) Merr.), rape (*Brassica napus* L.), and oranges (*Citrus sinensis* L.).The soil (0–15 cm) used had 8.90 g kg^{-1} of organic matter, 0.43 g kg^{-1}of total N, 0.39 g kg^{-1} of total P, 15.40 g kg^{-1} of total K, 30.2 mg kg^{-1} of available N, 15.4 mg kg^{-1} available P, 104.9 mg $kg^{-1}$of available K, and pH of 7.10 (1:2.5 soil/water suspension).

Experiment 1. Field experiment

The experiment was established on 30 October 2002. The experiment, comprising two hedge species (*A. fruticosa* and vetiver) and three cropping systems (sole soybean, sole hedge and soybean–hedge intercrop), was laid out in completely randomized design with three replicates. In the intercropping plots, *A. fruticosa* plants about 4 months old were established on one edge by seedlings prepared from nurseries and transplanted as a single row aligned E–W, with 20-cm spacing between hedge plants within the row. Vetiver plants were normally established beside seedlings such as *A. fruticosa*. Four parallel rows of soybean were planted at a spacing of 0.9 × 2.4 m starting 22 cm away from the hedgerow. Soybean was directly sown in rows 22 cm apart with 22 cm distance between plants in the row on 4 June 2003. Plots were 2.4 m long and 1.2 m wide. In the sole crop plots, the hedgerow row was replaced by a soybean row in the same plant populations as in the intercropped stands. In sole hedge plots, four parallel rows of hedge were planted in rows 30 cm apart with 30 cm between hedges in the row. Two crops were grown per year, December–May (winter wheat) and June–October (summer soybean). In December of each year, urea (120 kg N ha^{-1}), KCl (100 kg K ha^{-1}), and triple super-phosphate (46 kg P ha^{-1}) were applied to all plots as basal fertilizers. All plant species grew rain-fed without any supplementary irrigation.

Soybean was harvested on 12 September and hedgerows were pruned on 18 September. *A. fruticosa* and vetiver plants were pruned at a height of 25 cm and all prunings were collected and removed out of the plots.

Experiment 2. Pot experiment (^{15}N isotope labeled method)

A pot experiment was conducted to assess the belowground interactive effects on nitrogen availability for crops. The experiment was designed as a 3 × 2 completely randomized block with three replicates including hedges of different species and root barrier patterns. The hedge treatments were *A. fruticosa* and vetiver. To partition roots, the pots were divided into two compartments in proportion of 2:3 and then polyethylene sheet and nylon mesh (50 μm) were placed, and sealed to prevent water leakage. The smaller part of each pot was transplanted with three hedge plants as a single row and the other part with six soybean plants as two rows which were directly seeded. The rows adjacent to the hedgerow were called inner rows and the other rows were outer rows. In the pots with a sheet barrier, no interactions between hedges and soybean roots were possible, while in the treatment with a mesh barrier, direct root contact was impossible, but mycorrhiza penetration, nitrate interaction between the two compartments through mass flow and diffusion can occur. In the treatment without a barrier, hedges and soybean roots could intermingle.

Forty days after soybean planting, a 40-cm-long × 10-cm-deep trench between the hedgerow row and the inner rows of soybean was dug at a distance of 20 cm from the hedgerows for application of fertilizer. In the treatments with and without a mesh barrier, ^{15}N enriched CO $(^{15}NH_2)_2$ (approximately 10.35% atom excess) was uniformly hand-applied as a rate of 101.04 mg pot^{-1}. In the treatment with a sheet barrier, root contact and N movement were arrested as the hedge plants cannot capture the resources from the area of soybean; regular CO $(NH_2)_2$ was applied at the same rate (Fig. 1). Using the same air-dried soil as the field trial from the “A” horizon, which was the 0–15 cm depth, 150 kg (passed through 5 mm) was placed in each plastic pot with 75 × 50 cm placed above surface, and 75 × 44 cm in the bottom and 50 cm in height. The plants were supplied with ample water during the whole period. At soybean harvest, soybean stem and grain were carefully washed and oven-dried to constant weight. The total ^{15}N-lableled soybean N was measured on the basis of each pot.

N analysis of plant dry matter material

Soybean plants from each plot/pot were hand-harvested by row, and divided into leaf, stem and grain. The soybean and hedge samples were weighed,

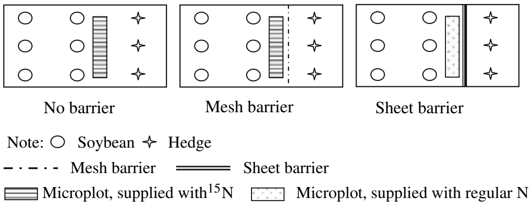

Fig. 1 Schematic representation of pot partition and N application

oven-dried and reweighed, to obtain dry weight conversion factors for each part. The dried plant samples were ground to pass 0.5 mm in a ball mill and then subjected to a semi-micro-Kjeldahl method as follows: 200 mg grain material, 200 mg stem leaf mixture with 5 ml H_2SO_4, 1.5 g K_2SO_4 and 0.15 g $CuSO_4$ were digested, respectively. Then this material was shaken to disperse the mixture homogenously and put in digestion tubes to react overnight. Distillates were collected with boric acid and titrated with sulfuric acid for total N. Titrated distillates were then concentrated until each contained approximately 1 g N l^{-1}, and analyzed for ^{15}N on a mass spectrometers.

The atmospheric abundance of ^{15}N (i.e., 0.3663 atom%) was used as background to calculate the atom % ^{15}N excess values of both soybean and hedge, which resulted in errors relative to the use as background of ^{15}N values from areas where no labeled fertilizer was applied (Vanlauwe et al. 2001; Rowe and Cadisch 2002). The error made by assuming atmospheric ^{15}N enrichment in control treatments was usually below 0.0037% (Yoneyama et al. 1993; Su et al. 1999).

The recovery of applied ^{15}N was calculated from above-ground biomass and ^{15}N contents of stem and grain, respectively. In order to study the effect of hedge intercrops on the N availability of fertilizers and %Ndff (Nitrogen derived from fertilizers) in experiment 2 were calculated from the enrichment data to determine the degree of interspecific competition for N as follows:

$$\begin{aligned} &{}^{15}\mathrm{N}\ \text{recovery}\ (\text{mg row}^{-1}) \\ &\quad = \text{mass}\ (\text{g row}^{-1}) \times \text{N concentration}\ (\%) \\ &\quad \times \text{atom\%}\ {}^{15}\mathrm{N}\ \text{excess}/100 \end{aligned}$$

$$\begin{aligned} \%\text{Ndff} = {} & (\text{atom\%}\ {}^{15}\mathrm{N}\ \text{excess}_{\text{sample}}/ \\ & \text{atom\%}\ {}^{15}\mathrm{N}\ \text{excess}_{\text{fertilizer}}) \times 100 \end{aligned}$$

Below-ground biomass of crop and hedges, and biomasses of hedge plants which were pruned at 25 cm above the ground were not determined. They could constitute a large part of total plant N recovery, more for *A. fruticosa* (root-to-shoot ratio 2.92–4.13; Li et al. 2004) than for vetiver (root-shoot-ratio 0.20–0.25; Liu et al. 2006) and soybean (ratio-shoot-ratio 0.12–0.36; Feng et al. 2001).

Calculations of Land Equivalent Ratio

The Land Equivalent Ratio (LER) is the most frequently used index to indicate intercropping advantage and can be applied to any form of intercropping (Willey 1979; Ofori and Stern 1987). It is an expression of the land required for production of the same yield in sole crops as compared to intercrops. In the present study, soybean yield and biomass were calculated for each plot as the sum of yields. In the intercropping treatments, crop yields were determined as a function of distance to the hedgerow. If the total yields of the different systems were compared (Table 1), the intercrop yield was calculated including the space occupied by the hedges, which reduced crop yields on a hectare basis. If crop yields of individual rows were compared with each other or the sole treatment (Fig. 2), the yield per row was calculated per hectare. The LER values were calculated as follows:

Table 1 Nitrogen yields of soybean and hedges in sole and intercropping systems (field experiment)

Values within one column followed by the same letter are not significantly different at $p < 0.05$ ($n = 3$)

Cropping system	Cultivated pattern	Soybean (g N m^{-2})	Hedge (g N m^{-2})	Total intercropping (g N m^{-2})
Vetiver–soybean	Sole	11.2a	16.7a	
	Intercropping	9.5a	18.4a	9.7
A. fruticosa–soybean	Sole	11.2a	19.8a	
	Intercropping	9.2a	21.8a	10.8

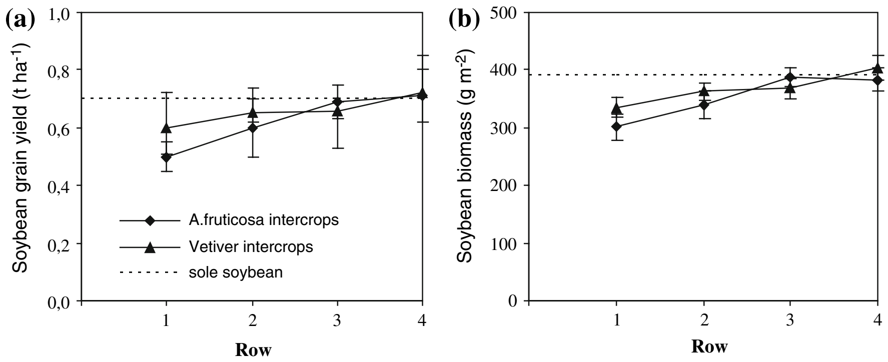

Fig. 2 Soybean grain yields (**a**) and aboveground biomass of soybean (**b**) when grown with *A. fruticosa* and vetiver plants, and a sole crop in Subtropical China. *Error bars* denote one standard error of the mean

$$L_S = Y_{\text{soybean}}\ \text{intercropping}/Y_{\text{soybean}}\ \text{sole}$$

$$L_H = Y_{\text{hedge}}\ \text{intercropping}\ /Y_{\text{hedge}}\ \text{sole}.$$

$$\text{LER} = L_S + L_H$$

Y_{soybean} intercropping and Y_{hedge} intercropping are the intercrop yields (N acquisition) and Y_{soybean} sole and Y_{hedge} sole are the sole yields (N acquisition) of soybean and hedge. L_s and L_H are the partial LERs for soybean and hedge, respectively, and represent the ratio of yields of soybean and hedge under intercropping, where LER > 1 indicates an advantage from intercropping, in terms of the use of environment resources for plant growth, and LER < 1 implies that resources were used more efficiently by sole crop than intercrops.

Statistical analysis

Statistical analyses were conducted by analysis of variance (GLM) with SAS version 8.1. Least significant difference was employed to determine the significance of treatment means at 0.05.

Results

Experiment 1

Soybean grain yield and biomass

Soybean grain yield in the *A. fruticosa*–soybean system, averaged across the intercropping, was 3.5 t ha^{-1}, significantly less than that (3.9 t ha^{-1}) in the sole soybean system. The slight decrease of soybean grain yield (3.7 t ha^{-1}) in the vetiver–soybean system as compared to the sole soybean crop was observed. There was no significant difference in yields between the *A. fruticosa*–soybean system and the vetiver–soybean system. Grain yields were severely depressed in rows adjacent to hedgerows in crop intercrops (Fig. 2a), particularly in the *A. fruticosa*–soybean system. The outer rows in two intercropping systems provided the greatest yield, which were equivalent to those of the sole soybean. There was no significant effect of row on yield in sole soybean. In general, the soybean yields in two contour intercropping systems were below the sole soybean.

The soybean biomasses in rows adjacent to the hedgerows in intercropping systems were overtopped by the hedgerows at soybean harvest (Fig. 2b). Distance from the hedgerow had an effect on plant growth; soybean biomasses in row 1 were shorter than those in rows 2, 3 and 4 in two intercropping systems. When the data for individual row were analyzed separately, the biomasses of soybean intercrops were shown to be lower than those in the sole soybean treatment. In the case of the biomass, the soybean biomasses under *A. fruticosa* species were lower than those under vetiver species. The result was consistent with the trend of yield variation of soybean as mentioned above. Absolute differences, however, were small between the *A. fruticosa*–soybean system and the vetiver–soybean system.

Overall, there were significant differences at harvest by treatment. The soybean in rows adjacent to the hedgerows in intercropping system grew much slowly than those in the outer rows of intercropping system or the sole soybean crop.

Nitrogen acquisition

The soybean N yield was reduced from 11.2 g N m^{-2} under sole condition to 9.5 g N m^{-2} under vetiver species and 9.2 g N m^{-2} under *A. fruticosa* species, whereas intercropping strategy enhanced the N uptake of vetiver (18.4 g N m^{-2}) and *A. fruticosa* (21.8 g N m^{-2}), compared with sole vetiver (16.7 g N m^{-2}) and sole *A. fruticosa* (19.8 g N m^{-2}) (Table 1). The total N acquisition of the *A. fruticosa*–soybean system was relatively higher than that of the vetiver–soybean system. However, no significant difference was observed in N acquisition between soybean and hedge under both intercropping and sole condition.

Utilizations of plant growth factors

Soybean under vetiver species attained greater partial LER values than with *A. fruticosa* species (Fig. 3). The performance ratios of soybean under vetiver species varied between 0.76 expressed as DM production and 0.72 expressed as N acquisition. When grown with *A. fruticosa*, the performance ratios of soybean were 0.72 and 0.70, respectively. The performance ratios (L_H) of vetiver (0.23 and 0.27, respectively) and *A. fruticosa* (0.24 and 0.27, respectively) were lower during the cropping season. Moreover, no matter what the performance ratios of soybean expressed either as DM production or N acquisition, the LER values were always smaller than 1.0 in two intercropping systems.

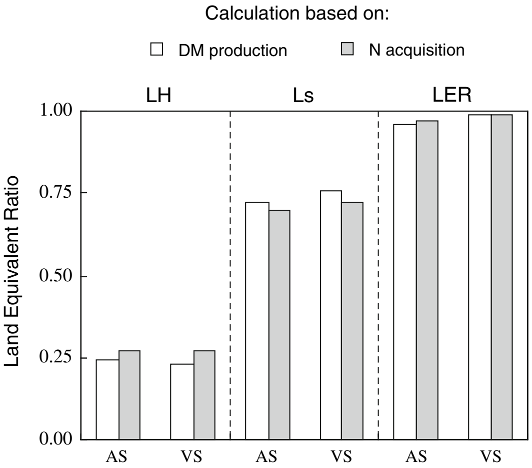

Fig. 3 Hedge and soybean partial LER (L_H and L_S) and LER. The calculations were based on total above-ground DM production and nitrogen acquisition in intercrops and sole plants

Experiment 2

Dry weight yield and nitrogen uptake in the pot experiment

The results from the field experiments showed that the present two systems had negative effect on the soybean growth and yield. To further evaluate the N benefits and interspecific interaction of the system, a pot experiment was designed and carried out to ascertain the mechanism of interspecific N uptake and allocation patterns.

The above-ground dry matter production and N uptake of soybean varied significantly with different hedge species and root barrier treatment. The effect of hedge species × root barrier interaction on soybean yields was significant at $p = 0.05$. In the *A. fruticosa*–soybean system, the highest N uptake was observed for intercropped soybean with a sheet barrier (2,404.9 mg pot^{-1}), followed by that with a mesh barrier (2,021.3 mg pot^{-1}), and then the lowest is that without a barrier (1,723.4 mg pot^{-1}) (Table 2). The dry matter per pot of soybean was lower under root interaction than under sheet partition conditions. Compared to sheet partition, root interaction resulted in a decrease of above-ground DM production of 28.3 and 15.9% when grown without and with a mesh barrier, respectively. In the vetiver–soybean system, the relative increments in N uptake under root interaction condition were 20.1 and 12.9%. The observed values of 129.7 g and 126.2 g per pot the dry matter of soybean within no barrier and mesh barrier treatments were significantly higher than that of a sheet treatment (120.6 g pot^{-1}) (Table 3). These data suggest that hedge species and root barrier patterns are the main factors affecting the growth of soybean.

In the present study, distance from hedgerow had an effect on soybean growth and yield. In the sheet barrier treatment, the DM productions of soybean in inner rows was 16.7 and 20.8% which were higher than those in outer rows, when grown with hedges of *A. fruticosa* and vetiver, respectively. The same trend kept true in no barrier and mesh barrier treatment

Table 2 Pattern of N uptake by soybean under *A. fruticosa* plants

Treatment	Row	Plant part	Shoot (g pot^{-1})	N (%)	N uptake (mg pot^{-1})	^{15}N atom % excess	Ndff (%)	^{15}N recovery (mg pot^{-1})
No barrier	Inner rows	Stem/leaf grain	21.8	1.254	190.6	0.128 (0.37%)	1.24 (0.03)	0.24 (0.01)
			6.9	6.564	452.9	0.213 (0.37%)	2.06 (0.03)	0.97 (0.02)
	Outer rows	Stem/leaf grain	39.7	1.126	329.9	0.053 (0.37%)	0.51 (0.03)	0.17 (0.02)
			10.2	6.048	750.0	0.025 (0.37%)	0.24 (0.03)	0.15 (0.02)
		Total plant	72.6a		1,723.4a		4.05 (0.12)	1.53 (0.07)
Mesh barrier	Inner rows	Stem/leaf grain	33.6	1.195	260.5	0.340 (0.37%)	3.29 (0.03)	0.78 (0.01)
			11.6	6.251	718.9	0.742 (0.37%)	7.17 (0.03)	5.37 (0.03)
	Outer rows	Stem/leaf grain	36.4	1.108	270.4	0.105 (0.37%)	1.01 (0.03)	0.28 (0.01)
			12.4	6.172	771.5	0.113 (0.37%)	1.09 (0.03)	0.87 (0.03)
		Total plant	94.0b		2,021.3b		12.56 (0.12)	7.30 (0.08)
Sheet barrier	Inner rows	Stem/leaf grain	47.5	1.156	380.3			
			14.6	6.383	931.9			
	Outer rows	Stem/leaf grain	40.1	1.087	290.2			
			13.1	6.126	802.5			
		Total plant	115.3c		2,404.9c			

Numbers in parenthesis indicate maximum errors made by using 0.3663 atom% as background

Different letters in columns indicate significant differences between treatments at $p < 0.05$ ($n = 3$)

Table 3 Pattern of N uptake by soybean under vetiver plants

Treatment	Row	Plant part	Shoot (g pot^{-1})	N (%)	N uptake (mg pot^{-1})	^{15}N atom % excess	Ndff (%)	^{15}N recovery (mg pot^{-1})
No barrier	Inner rows	Stem/leaf grain	57.2	1.983	910.2	0.204 (0.37%)	1.97 (0.03)	1.85 (0.04)
			15.3	6.621	1013.0	0.296 (0.37%)	2.86 (0.03)	2.99 (0.04)
	Outer rows	Stem/leaf grain	44.8	1.156	369.9	0.095 (0.37%)	0.92 (0.03)	0.36 (0.02)
			12.4	5.984	742.0	0.123 (0.37%)	1.19 (0.03)	0.91 (0.03)
		Total plant	129.7ab		3,035.1ab		6.94 (0.12)	6.11 (0.13)
Mesh barrier	Inner rows	Stem/leaf grain	53.5	1.336	530.4	0.537 (0.37%)	5.33 (0.03)	2.82 (0.03)
			14.2	6.382	912.6	1.052 (0.37%)	10.48(0.03)	9.53 (0.03)
	Outer rows	Stem/leaf grain	46.7	1.207	420.0	0.127 (0.37%)	1.27 (0.03)	0.53 (0.02)
			11.8	6.107	720.5	0.136 (0.37%)	1.35 (0.03)	0.97 (0.02)
		Total plant	126.2ab		2,853.5ab		18.43(0.12)	13.85(0.11)
Sheet barrier	Inner rows	Stem/leaf grain	52.6	1.467	579.5			
			13.4	6.452	858.1			
	Outer rows	Stem/leaf grain	41.9	1.096	320.0			
			12.7	6.063	770.0			
		Total plant	120.6a		2,527.6a			

Numbers in parenthesis indicate maximum errors made by using 0.3663 atom% as background

Different letters in columns indicate significant differences between treatments at $p < 0.05$ ($n = 3$)

when soybean grew with vetiver. But the DM productions of soybean under *A. fruticosa* in inner rows were 42.4 and 7.3%, which were lower than those in outer rows in no barrier and/or mesh treatment, respectively. In relation to support hedge, a root barrier significantly affected the above-ground

Table 4 Pattern of N uptake by hedgerow intercrops

Treatment	Hedgerow	Shoot (g pot^{-1})	N (%)	N uptake (mg pot^{-1})	^{15}N atom % excess	Ndff (%)	^{15}N recovery (mg pot^{-1})
No barrier	*A. fruticosa*	87.4a	1.842	1,609.94a	0.399 (0.37%)	3.86 (0.03)	6.42 (0.06)
	Vetiver	285.1e	0.670	1,906.15b	0.729 (0.37%)	7.04 (0.03)	13.90(0.07)
Mesh barrier	*A. fruticosa*	98.5b	1.908	1,878.89ab	0.472 (0.37%)	4.56 (0.03)	8.87 (0.07)
	Vetiver	250.7de	0.706	1,773.47ab	0.250 (0.37%)	2.42 (0.03)	4.43 (0.06)
Sheet barrier	*A. fruticosa*	110.1c	1.934	2,129.35c			
	Vetiver	205.9d	0.743	1,532.81a			

Numbers in parenthesis indicate maximum errors made by using 0.3663 atom% as background

Different letters in columns indicate significant differences between treatments at $p < 0.05$ ($n = 3$)

biomasses of hedges (Table 4). The biomass of *A. fruticosa* increased as follows: no barrier (87.4 g pot^{-1}) < mesh barrier (98.5 g pot^{-1}) < sheet barrier (110.1 g pot^{-1}). For vetiver, the sequence was in the order of no barrier (285.1 g pot^{-1}) > mesh barrier (250.7 g pot^{-1}) > sheet barrier (205.9 g pot^{-1}). Likewise, total uptake of N by hedge species was also affected by a root barrier. The highest quantity of N taken up by *A. fruticosa* was found in the sheet barrier treatment, as it is the major contributor to total above-ground biomass. In contrast, vetiver absorbed much larger quantity of N in the no barrier treatment.

Enrichment of ^{15}N in plant and uptake of applied N

The uptake of fertilizer ^{15}N by soybean differed according to root barrier pattern and hedge species. Irrespective of hedge species intercrops, ^{15}N enrichment values detected in soybean in the mesh barrier treatment were higher than those observed in the no barrier treatment (Tables 2, 3). At the end of the experiments, the ^{15}N uptakes by soybean from the applied ^{15}N were only 1.53 and 7.30 mg pot^{-1} under *A. fruticosa* species and 6.11 and 13.85 mg pot^{-1} under vetiver species when grown without a barrier and with a mesh barrier, respectively.

Compared to soybean, the relatively higher ^{15}N enrichment of *A. fruticosa* was observed in the mesh barrier treatment, whereas that of vetiver was noted in the no barrier treatment. The quantities of ^{15}N from the applied fertilizer by *A. fruticosa* were 6.42 mg pot^{-1} in the no barrier treatment and 8.87 mg pot^{-1} in the mesh barrier treatment, respectively. For vetiver, the quantities of ^{15}N from the applied fertilizer were 13.90 mg pot^{-1} in the no barrier treatment and 4.43 mg pot^{-1} in the mesh barrier treatment, respectively. A comparison of the magnitude of absorption of the applied fertilizer N by soybean crops and support hedges indicates that root contact is the main factor affecting N uptake distribution.

Discussion

Results of this experiment clearly showed that the hedge species suppressed soybean growth and yield in contour hedgerow intercropping systems as compared to the sole soybean system (Fig. 2). As expected, distance from the hedgerow had an impact on the vegetative growth of soybean with a trend of decreasing growth and yield with closer proximity to the hedgerow, which is a good indicator of competition for nutrients, water and light imposed by the hedge plants. The soybean grew better under vetiver than under *A. fruticosa*. However, there was no significant difference in the two intercropping systems. Similarly, Kang et al. (1999) reported that hedge species (*Gliricidia*, *Lencaena*, *Alchornea* and *Dactyladenia*) in alley cropping systems showed little effect on cowpea yield in the humid tropical zone, and cowpea yields under *Alchornea* and *Dactyladenia* were higher than those under *Gliricidia* and *Lencaena*. They attributed lower cowpea yield to the fact that alley cropping of food legumes with woody legumes showed conflicting results. Similar observations were obtained by Dhyani and Tripathi (1999) who showed that total soybean grain yield was reduced with alder, mandarin and cherry in north-east India. However, Ghosh et al. (2006) reported that the suppressive effect of pigeon pea on intercrop soybean was not significant, and soybean benefited in association with pigeon pea. In our trial, the lower soybean yield may be attributed to the fact that hedge plants exhausted the soil N quickly during early soybean growth, since hedge species grow faster during the long rains. Although soybean is also a fast growing plant, soil N was not sufficient to meet soybean N requirement. These may be some of the reasons in the present study why soybean yield was reduced. In the present study, soybean was not the dominant component in the two present intercropping systems (Fig. 3). LERs were smaller than 1, which indicates a better utilization of the environment resources by the sole crops compared to the intercrop crops. In conformity with the present study, Gruenewald et al. (2007) obtained a similar *R. pseudoacacia–M. sativa* intercrop LER value (0.98) based on DM production. They attributed the yield reduction of *M. sativa* growing next to the hedgerows to above- and below-ground interactions of trees and crops. This disadvantage was also partly demonstrated in our study by the increase of soybean yields with increasing distance from hedgerows. Likewise, the yield reduction can be explained by the fact that the soybean rows adjacent to the hedgerow showed poorer N uptake than those in the rest of crop intercrops or in the sole crop (data not shown). In other studies, they attributed the intercropped advantage to different above- and below-ground growth habits and morphological characteristics of intercrop components causing a greater efficiency in the utilization of plant growth resources (Willey 1979; Ofori and Stern 1987; Fukai and Trenbath 1993; Hauggaard-Nielsen et al. 2001). As a result, interspecific interactions are the main factors affecting the growth of intercrop components.

In agroforestry systems, the yield reduction of crops is often presumed to be associated with competition exerted by the hedges for essential growth resources such as nutrients, light and water (Van Noordwijk et al. 1996; Rao et al. 1998). In the present systems studied, the N accumulation of the sole hedges of *A. fruticosa* and vetiver yielded up to 90.8 and 90.7% of that of the intercropped hedges, respectively. It indicates that hedge plants are able to benefit from the cropping strategy. In addition, it should be noted that biomass and N acquisition by roots were not assessed in the present study and total N sequestration in plants was underestimated. Therefore, more complete monitoring would be needed to validate this work.

Below-ground interactions are the most important aspects concerning yield reduction in the semi-arid tropics where water is the prime factor limiting crop growth (Ong et al. 1991). Xiao et al. (2004) also reported below-ground interactions were the main factor affecting plants growth in the wheat–fababean intercropping system in China. Hellin and Haigh (2002) attributed the higher maize yield to soil water conservation by vetiver in the vetiver–maize system in Honduras, Africa. In the present study area, rainfall is abundant, but seasonal drought is also noticeable. So competition for water among component species cannot be ruled out. Like water competition, hedges may compete for nutrients, which alter soybean growth and yield. Some studies have reported that the root barriers can reduce or eliminate below-ground competition for N (Singh et al. 1989; Samuel et al. 2004). Livesley et al. (2002) also stated that in the absence of interspecies root competition and root allelopathy, such studies increased crop yields to levels comparable with those of a sole crop.

As hypothesized, the presence of the barriers had significant positive effects on the growth of soybean crops in the *A. fruticosa*–soybean system. Soybean yields, for example, in the treatment without root barrier were 28 and 38% lower than those in the treatments with a mesh barrier and a sheet barrier, respectively. Similarly, stem soybean biomass was also the lowest without root barrier followed by that with a mesh barrier and then a sheet barrier. In addition, the lowest biomass of *A. fruticosa* in the absence of barrier was also found. In the treatment with a sheet barrier, N acquisitions in soybean rows bordering *A. fruticosa* were higher than those in outer rows of crop intercrops, but the opposite trend was observed in the treatments with no barrier and a mesh barrier. This indicates that N addition has an additive effect on soybean growth, when water was not limiting, but it plays only a minor role relative to below-ground interactive effects between soybean and *A. fruticosa*. The percent of applied ^{15}N in *A. fruticosa* was only 3.86 lower without root barrier treatment than that of a mesh treatment (4.56). For soybean, the percent was 4.05 without root barrier treatment and 12.56 with mesh treatment, respectively. Although below-ground competition from *A. fruticosa* might lead to lower percent of applied ^{15}N in soybean, the lower N uptake from applied N in *A. fruticosa* in the absence of a root barrier is not fully understood; the lower N acquisition was also found in pigeon pea. Ghosh et al. (2006) attributed the lower N acquisition to N deficiency and soil N exhaustion by its companion soybean crop before soybean harvest. Soybean is a stronger competitor in their study, whereas soybean is a weaker competitor in our study as stated above. The reason for different results is not clear, although they are a legume–legume intercropping system. Some other studies suggested that crop growth was limited by factors other than N, like interference interaction (Jose et al. 2004), the particular nutrient (Ghosh et al. 2006), water (De Costa and Surenthran 2005) and root system dynamics (Mekonnen et al. 1999). In our study, some indirect evidence suggested that dynamics in root systems played an important role in the growth of soybean and hedges. In addition, interference interaction through allelopathy cannot be ruled out as a factor that nullified the edge effect and led to poor vegetative development and lint yield for soybean in rows adjacent to *A. fruticosa* in no barrier treatment and in the field experiment. Although not of the genus *Juglans*, *A. fruticosa* does produce phenolic compounds (Ohyama et al. 1998) which could be inhibitors (Blum et al. 1993). Some allelochemicals, such as butanedioic acid, phenol, benzoic acid, 2-methy-phenol, 2-methoxy-4-vinylphenol, etc., have also been isolated from soybean (Han et al. 2002). However, soybean and/or *A. fruticosa*'s sensitivity to these substances mentioned above is not known. These factors should therefore be studied further.

In the vetiver–soybean system, though root barriers were also effective in reducing (mesh barrier) and/or eliminating (sheet barrier) below-ground competition for fertilizer N, soybean still benefited in association with vetiver by root contact. Soybean N acquisitions in inner rows were higher than those in outer rows. The result is in agreement with our finding that N addition had additive effects on soybean growth as stated above. The percent of N from the labeled fertilizer in soybean were 6.94 and 18.43 in no barrier and mesh barrier treatment, respectively, and those of vetiver were 7.04 for the former and 2.42 for the latter, respectively, which may be an indication of vetiver competitive dominance over the soybean. Although soybean is a leguminous crop, the agronomic energy requirement for manure and fertilizer application was relatively high (Mandal et al. 2002). It is apparent that soybean in the absence of root barriers took up more of their N from the N present in the soil. At soybean maturity, most of their N is accumulated in the edible parts that are usually harvested and not returned to the soil, and this could lead to soil nutrients deficit which is disadvantageous to agricultural development. A comparison of the magnitude of absorption of fertilizer N by the soybean and vetiver in absence of root barriers suggests that vetiver can benefit from the fertilizer applied to the neighboring soybean. Similarly, Wahid et al. (2004) also observed that erythrina support tree absorbed much larger quantities of fertilizer N applied to black pepper vine in a black pepper–erythrina system, because of the encroachment of erythrina support tree into the root zone of black pepper vine. Obviously there is overlapping of the foraging zones of soybean and vetiver in field experiments and in the absence of root barrier treatment because of their close planting in the present study. However, the results stated by Tscherning et al. (1995) suggested that vetiver had the least competitive root system, with the shortest root length in the upper 40 cm of the profile and a root distribution that concentrated closely to each side of the grass barrier. An important difference between our study and the study by Wahid et al. (2004) was that we evaluated absorption and partition of applied ^{15}N in pots. Root growth of hedges and N leaching were influenced to some extent in the present experiments.

Overall, two mechanisms contribute to low fertilizer N recovery in plants by the intercropping systems in the present study: (1) biomass and ^{15}N acquisition by roots were not assessed in our study, and (2) below-ground ecological interactions (resource competition, plant competition and interference competition) influenced N uptake. For example, using a maximum estimate for root–shoot ratios (Feng et al. 2001; Li et al. 2006) and total N recovery would increase 0.5–4.9% (soybean), 26.2–36.1% (*A. fruticosa*) and 1.0–3.5% (vetiver). These calculations assume similar N concentrations in roots as in above-ground biomass which is most likely much smaller as demonstrated by McGrath et al. (2000). Obviously, total N recovery estimated in *A. fruticosa* significantly increases, whereas the conclusions about the N uptake distribution would be not affected by neglecting root N contents in the specific ecosystem. The lower N recovery (8.15 mg pot^{-1}) in *A. fruticosa*–soybean intercropping system may be possibly due to interference competition (allelopathy) as discussed above. And poor N recovery might be a result of soybean rooting volume reduced because of the presence of *A. fruticosa* or vetiver roots. Likewise, the lower N recovery may be attributed to a larger uptake of N by *A. fruticosa* and vetiver in agroforestry systems. As we all know, the delta ^{15}N values for soil and plants were typically between 0 and 10, rarely above 10 (Yao et al. 1990; Yoneyama et al. 1993; Su et al. 1999). In order to assure the substantiality of ^{15}N enrichment, a maximum error in delta units was used to estimate the control, and the value of atom % ^{15}N excess would be in turn have modified particularly those samples with low amounts of enrichment (Tables 2–4). The fertilizer N recovery of samples would decrease more or less. However, the conclusions about the interspecific interactive effects on N uptake between hedge and crop plants would not be influenced to a great extent.

In addition, above-ground interactions in agroforestry such as microclimatic modification and light interception have been shown to also be factors in affecting yield. For example, Kort (1998) and Brandle et al. (2000) reported that planting windbreaks or shelterbelts improved crop quality and yield within the sheltered area. Nissen et al. (1999) reported that shading by associated tree species decreased the yield of cabbage (*Brassica oleeracea*). Unfortunately, in the present study, we had no convincing way to demonstrate above-ground interactions as important factors affecting the growth of soybean. Nevertheless, in the presence of the sheet barrier, soybean yield and biomass under *A. fruticosa* were lower than those under vetiver (Tables 2, 3). In field experiments, a similar phenomenon has been also observed (Fig. 2). Thus, it can be assumed that soybean growth difference under hedges of *A. fruticosa* and vetiver is related to above-ground interactions.

Conclusions

Based on the results obtained, we conclude that hedge species used in contour hedgerow intercropping system in terrace in subtropical China clearly decreased the yields of associated soybean crops. This was partly attributed to interspecific interactions, particularly below-ground interactions. Nitrogen addition is undoubtedly required to maintain the existing soybean yield in the current experiment site. Below-ground competition for N was suspected as one of the reasons for the observed soybean yield reductions in the *A. fruticosa*–soybean intercropping system, and our results indicated that N was not clearly the dominant factor for the observed yield reduction in that system. Competition from vetiver was alleviated to a great extent by the application of fertilizer N, and soybean may benefit in association with vetiver to a certain extent when water and light are not limited. The insertion of a mesh barrier and a sheet barrier to separate the component root systems may not be necessary to achieve similar results or be practical for agroforestry practitioners. The results of our study indicate that, in subtropical zone intercropping, annual or biannual root pruning of the hedge species and/or increasing the distance between hedgerow and soybean crops may be advantageous to alleviate nutrient stress of the associated agronomic species. For the *A. fruticosa*–soybean intercropping system that include soybean in similar soils, trenching or deep disking parallel to the hedgerow row may be beneficial for providing satisfactory crop yields; for the vetiver–soybean intercropping system, the partition step is not needed.

Acknowledgements We gratefully acknowledge the Major State Basic Research Development program of the People's Republic of China (Project number 2007CB407201) and the National Nature Science Foundation of China (Project number 40271073) for financial support. We are also grateful to Dr Yuan Yongping from Sedimentation National Laboratory for her revision, and two anonymous reviewers for their helpful comments and suggestions that improved the manuscript greatly.

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