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Competitive interactions in Ginkgo and crop species mixed agroforestry systems in Jiangsu, China

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Abstract Intercropping Ginkgo and crop species in southern China is receiving increasing attention because it offers potential advantages for resource utilization, higher economic income to farmers and increased sustainability in crop production, We carried out a 2-year field intercropping system composed of Ginkgo with wheat, broad bean, and rapeseed, respectively, to determine the competitive interactions between the different species, and productivity and the economic yield of each intercropping system. The density of Ginkgo and crop species was varied systematically in a two-way density matrix composed of three monoculture densities and nine intercropping of all possible pairwise combinations of monoculture densities. Intercropping systems were assessed on the basis of several intercropping indices such as land equivalent ratio, relative crowding coefficient, relative competition intensity and vector competition analysis. The results showed that the combined biomass production of the component crop species was significantly greater in the Ginkgo/crop mixtures than in monocultures crops (Ginkgo, broad bean, wheat, and rapeseed). Ginkgo: rapeseed ratio 24:12, Ginkgo: bread bean ratio 24:5, and Ginkgo: wheat ratio 24:200 had the best total biomass production. Ginkgo: rapeseed (and broad bean) ratio 24:5 and Ginkgo: wheat ratio 24:200 in respective Ginkgo/crop mixtures had the maximum economic yield. Vector competition analysis showed that Ginkgo/rapeseed mixture exhibited an antagonistic interaction type and therefore is not suitable for intercropping. Ginkgo/broad bean mixture demonstrated the most beneficial effects among the three intercropping systems.

Keywords Intercropping · Wheat · Broad bean · Rapeseed · Relative competition intensity · Land equivalent ration (LER) · Relative crowding coefficient (RCC) · Vector competition analysis

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Introduction

Ginkgo (*Ginkgo biloba* L.) has been used as a medicinal remedy in China for several thousand years. With the increasing demand for Ginkgo nuts and leaves for medicine making, farmers in Jiangsu Province, China, have increasingly been growing Ginkgoes intercropped with annual crop species to sustain an optimum combined yield. Large areas of Ginkgo and crop intercropping agroforestry systems have been established in southern China in the past 20 years, but there have been few studies of Ginkgo/crop competition and mixtures (Cao et al. 2009). Knowledge of possible interactions, competitive abilities, and growth strategies of Ginkgo and companion annual crop species in intercropping systems is fundamental to our understanding of optimum Ginkgo and crop combinations. To provide farmers with scientific advice and management technique, it is necessary to study the competitive ability of intercropping plant components and to explore optimum Ginkgo/crop intercropping patterns.

Studies of tree-crop interactions have yielded conflicting results. For instance, Reyes et al. (2009) reported that intercropping black pepper and cardamom produced 3.9 times more than in monoculture. Maghembe et al. (1986) and Young (1997) reported benefits of trees for crops because of synergistic effects; whereas others have concluded that crop yield under trees was reduced because of competition (Rao et al. 1991; Chamshama et al. 1998). Imo and Timmer (2000) concluded that tree-crop interactions are not constant, and may be affected by several factors, including total planting densities, component combinations, climatic and soil conditions, and management regimes. Thus, systematic methods are required to quantify the overall interaction effects in different agroforestry systems.

Two main approaches, replacement series and factorial experiments, have been employed to quantify the interactions between plant species. Some plant biologists have noted the limitation of replacement series models (Jolliffe et al. 1984; Firbank and Watkinson 1985a, b; Willey 1985; Rejmanek et al. 1989). However, resource complementarity, competitive ability, and severity of competition may all be affected by the density of each component in the mixture. In this study, we experimentally manipulated the densities of Ginkgo and crop systematically to examine the competitive interactions between Ginkgo and crop species.

The main objectives for the study are to: (1) examine the effects of mixed species systems on leaf morphological parameters of the components species; (2) explore relative competitive ability of crop components in the system; and (3) identify optimum Ginkgo: crop ratios. The three hypotheses to be tested were: (1) there is a mixture and component species effect on growth, yield and biomass allocation; (2) the competitive ability of component species in the three Ginkgo/crop mixtures differs, and is affected by planting density; and (3) mixtures can achieve a higher combined yield than pure Ginkgo stands and pure crop system, because of niche differentiation in the mixtures.

Materials and methods

Experimental design

A factorial experiment was employed in this study. Two factors (i.e., Ginkgo and a crop species) each at four levels of densities (i.e., plants per m^2) were varied in three mixtures (i.e., Ginkgo/wheat, Ginkgo/broad bean, and Ginkgo/rapeseed), giving three 4×4 factorial experiments with 16 treatments (factor combinations or Ginkgo: crop ratios) (Table 1). The treatments were arranged in a completely randomized design with three replicates. Each mixture thus had 48 ($4 \times 4 \times 3$) experimental units (plots) and the study

Table 1 Factorial combinations of Ginkgo and three intercropped crop species (plants m^{-2}) employed in the field factorial experiment trial at Taixing Forest Station, Taixing, Jiangsu, China

Ginkgoes per m^2	0	8	16	24
Ginkgoes/rapeseed mixture				
Rapeseeds per m^2				
0	0/0	8/0	16/0	24/0
5	0/5	8/5	16/5	24/5
8	0/8	8/8	16/8	24/8
12	0/12	8/12	16/12	24/12
Ginkgoes/wheat mixture				
Wheat per m^2				
0	0/0	8/0	16/0	24/0
200	0/200	8/200	16/200	24/200
400	0/400	8/400	16/400	24/400
600	0/600	8/600	16/600	24/600
Ginkgoes/broad beans mixture				
Broad beans per m^2				
0	0/0	8/0	16/0	24/0
5	0/5	8/5	16/5	24/5
8	0/8	8/8	16/8	24/8
12	0/12	8/12	16/12	24/12

had a total of 144 (48 × 3) plots. One plot occupied 2.0 m × 1.5 m of area. The outer 0.2 m of each plot was an unmeasured buffer. The field experiment was conducted on sandy soil with medium fertility at Taixing Forest Station, Taixing, Jiangsu between January 2000 and October 2001. Soil from a local nursery with no fertilization was considered to be nutrient poor. Medium nutrient level was created by adding a commercial NPK fertilizer [12(N)–11(P_2O_5)–18(K_2O)] and an organic fertilizer (60% organic matter, 5% organically bound N, 0.28% soluble N, 4.5% P_2O_5, 2.8% K_2O and 2.8% MgO), a trademark of Nanjing Fertilizer Ltd., to the upper layer (0–28 cm) of the soil. The commercial NPK fertilizer at a rate of 500 kg ha^{-1} and the organic fertilizer at 650 kg ha^{-1} were applied to create the medium nutrient level before planting in January 2000.

The species chosen for this study were the deciduous broadleaf Ginkgo (*G. biloba* L.), broad bean (*Vicia faba* L.), rapeseed (*Brassica napus* L.), and wheat (*Triticum aestivum* L. cv. "Feng Shou No. 2"). In January 2000, two-year-old Ginkgoes (60.1 cm mean height) were planted at densities of 0, 8 (35 × 35 cm), 16 (25 × 25 cm) and 24 (20 × 20 cm) per m^2. On November 16, 2000, about one-month-old wheat, broad beans and rapeseeds from the farm land of Taixing Forest Station were transplanted into the experiment plots in mixture with Ginkgoes at the density combinations given in Table 1. During the experiment, the site was kept free of other vegetation competition by regular hand weeding, and frequent watering to provide relatively uniform soil moisture (about 80% of field capacity).

Leaf area, and biomass measurements

Just before harvesting in October 2001, all leaves of four-year-old Ginkgo were removed and put in plastic bags for leaf area and biomass measurements. Leaf area (one sided) was measured using a LI-3100 area meter (LI-COR Portable Area Meter, Lincoln, Neb., USA). The leaf area meter was calibrated by passing a known-area calibration disc through the machine.

All crop plants in the experimental plots were harvested when they were mature, including aboveground biomass and the excavation of crop root systems. Rapeseed, wheat, and broad bean were harvested in mid May, mid June, and late June 2001, respectively. After harvesting, all crop plants were separated into root, shoot (stem and leaf) and seed to determine dry mass of each biomass components. In each plot, a sample of ten Ginkgo seedlings was harvested from 10 to 14 October 2001. These seedlings were carefully excavated and measured for individual seedling leaf, stem, and root biomass. All biomass samples of the seedling components were oven-dried at 70°C for 48 h and then weighed to the nearest 0.01 g. Thick Ginkgo stems were split to facility the drying.

Root/shoot ratio and specific leaf area

Root/shoot ratio (RSR) and specific leaf area (SLA) were calculated according to the following formula: SLA = L_A/L_W, and RSR = R_W/S_W, where L_A is leaf area, L_W is leaf dry weight, R_W is root weight, S_W is shoot (stem and lateral branch) weight. Lead area index (LAI) was calculated as the leaf area over per m^2 land area.

Relative crowding coefficient (RCC), land equivalent ratio (LER)

Relative crowding coefficient which is a measure of the relative dominance of one species over the other in a mixture (De Wit 1960) was calculated as:

$$RCC_{ij} = \left(Y_{ij}/Y_{ii}\right)/\left(Y_{ji}/Y_{jj}\right)$$

where Y_{ii} and Y_{jj} is the yields per unit area of species i and j (as Ginkgo and crop species in this study) grown in pure stands, respectively, and Y_{ij} and Y_{ji} are the yields of the species when grown in intercropping. Relative competition intensity (RCI) was simply calculated as (Grace 1995):

$$RCI = (Y_{pure} - Y_{mix})/Y_{pure}.$$

The LER is the ratio of the area under pure stand to the area under intercropping needed to produce equal amount of yield at the same management level. LER is the most widely accepted index for evaluating the effectiveness of all forms of mixed cropping and has been extended to agroforestry by some researchers (Rao et al. 1990, 1991). In particular, LER indicates the efficiency of intercropping for using the resources of the environment compared with monoculture (Mead and Willey 1980; Dhima et al. 2007). LER was calculated as:

$LER = Y_{gc}/Y_g + Y_{cg}/Y_c.$

where Y_g and Y_c are the yields of Ginkgo and crop species in pure culture, respectively, and Y_{gc} and Y_{cg} are the yields of Ginkgo and crop species, respectively, as mixtures. If the ratio is greater than 1.0, intercropping is advantageous, while less than 1.0 indicates a disadvantage.

Vector competition analysis

We used the vector competition analysis methods proposed by Imo and Timmer (1998, 2000) to identify antagonistic, synergistic and compensatory relationship between Ginkgo and crop species. Inter-species interactions are evaluated relative to a reference plant status normalized to 100% (biomass in pure culture, Mead and Mansur 1993; Imo and Timmer 2000). To evaluate and visually present the possible interactions between Ginkgo and the three crop species, the biomass values of Ginkgo and the three crops: wheat, rapeseed, and broad bean were expressed as percentages of the values for Ginkgo and crop pure plantations, respectively.

Statistical analysis

Three-way analysis of variance (ANOVA) was conducted on all growth, biomass parameters and competition indices to test the effects of plant combinations and density using the GLM procedure in the SYSTAT statistical package (SPSS Inc. USA). The significance level was set at $\alpha = 0.05$. If significant differences were detected among the levels of density, then a multiple comparison procedure (Tukey test) was used.

Results

Leaf characteristics

Leaf biomass is the main objective of Ginkgo plantation. Gingko and crop density exerted a significant ($P < 0.01$) influence on leaf area per Ginkgo seedling (Table 2). A significant Ginkgo density × crop density interaction was detected ($P < 0.001$) in each of the Ginkgo/crop mixtures. Compared to monoculture, mixtures significantly decreased leaf area per seedling (LAS) of Ginkgo. LAS declined significantly as Ginkgo and crop density increased. There was no significant difference in LAS among the three mixtures ($P = 0.63$). This means that Ginkgo leaf production was not affected by intercropping with the three crop species.

Changing density of Ginkgo and crop species had a strong ($P < 0.001$) effect on Ginkgo leaf area index (leaf area per unit land area, LAI). LAI increased significantly ($P < 0.05$) as Ginkgo density increased. In contrast, LAI decreased rapidly as crop density increased within each Ginkgo density (Table 2). LAI in the Ginkgo/wheat and Ginkgo/broad bean mixture was slightly higher than the Ginkgo/rapeseed mixture.

Ginkgo density had no significant ($P = 0.063$) effect on its SLA, but crop density hade a significant ($P < 0.05$) effect on Ginkgo SLA. SLA increased with increasing crop density (Table 2). There was a stronger response of SLA to the change of crop density for the Ginkgo/rapeseed and Ginkgo/wheat mixtures than for the Ginkgo/broad bean mixture ($P = 0.032$). SLA in Ginkgo/rapeseed and Ginkgo/wheat mixtures increased more rapidly than the Ginkgo/broad bean mixture as crop density increased at each corresponding Ginkgo density. However, there was only a smaller difference in SLA among crop density treatments when grown with broad bean (Table 2), possibly because of nitrogen-fixing contribution from the broad beans. Average SLA followed the pattern of Ginkgo/rapeseed > Ginkgo/wheat > Ginkgo/broad bean mixture ($P < 0.05$).

Ginkgo biomass allocation

The similar patterns of Ginkgo biomass allocation were found for the three Ginkgo/crop mixtures (Fig. 1). Leaf accounted for about 17% of total biomass, stem and root each accounted for about 41 and 42% of total biomass, respectively. There was no significant ($P = 0.072$) interaction between Ginkgo density and crop density. There was a marked ($P < 0.001$) difference in all biomass components among the three Ginkgo/crop mixtures (data not presented).

Increased Ginkgo and crop density resulted in a slight increase in Ginkgo's RSR, suggesting that an increase in the density of crop components caused a stronger competition for soil resources between Ginkgo and crop species (Wilson 1988). Mean RSR pooled from nine Ginkgo: crop ratios followed an order of Ginkgo/rapeseed > Ginkgo/wheat > Ginkgo/broad bean mixture ($P = 0.035$, Table 3), inferring that the

Table 2 Leaf area per seedling (LAS), leaf area of per m^2 of land area (LAI) and specific leaf area (SLA) for different Ginkgo: crop ratios in the three mixtures in the Taixing field factorial experiment: Ginkgo/rapeseed; Ginkgo/broad bean; and Ginkgo/wheat

Ginkgo	LAS			LAI			SLA		
	8	16	24	8	16	24	8	16	24
Ginkgo/rapeseed mixture									
Rape seed									
0	0.255	0.193	0.173	2.05	2.98	4.16	75	76	74
	(0.04)	(0.02)	(0.03)	(0.36)	(0.24)	(0.60)	(5)	(5)	(8)
5	0.180	0.175	0.170	1.46	2.85	4.03	90	91	90
	(0.02)	(0.04)	(0.02)	(0.24)	(0.21)	(0.36)	(4)	(5)	(6)
8	0.165	0.163	0.151	1.23	2.38	3.52	93	93	92
	(0.05)	(0.01)	(0.02)	(0.28)	(0.12)	(0.48)	(8)	(7)	(7)
12	0.160	0.154	0.148	1.20	2.48	3.50	110	113	112
	(0.02)	(0.02)	(0.03)	(0.10)	(0.48)	(0.24)	(10)	(8)	(5)
Ginkgo/broad bean mixture									
Broad bean									
0	0.254	0.193	0.168	2.03	2.96	4.03	77	79	79
	(0.02)	(0.03)	(0.03)	(0.35)	(0.25)	(0.36)	(8)	(6)	(7)
5	0.196	0.190	0.160	1.74	2.92	3.85	83	84	86
	(0.03)	(0.02)	(0.01)	(0.21)	(0.26)	(0.23)	(4)	(4)	(6)
8	0.193	0.168	0.152	1.73	2.86	3.72	88	89	88
	(0.03)	(0.02)	(0.02)	(0.26)	(0.26)	(0.40)	(6)	(4)	(8)
12	0.151	0.157	0.143	1.45	2.53	3.34	91	90	91
	(0.04)	(0.04)	(0.04)	(0.20)	(0.31)	(0.17)	(6)	(5)	(5)
Ginkgo/wheat mixture									
Wheat									
0	0.259	0.196	0.168	2.12	3.25	4.16	76	77	76
	(0.04)	(0.03)	(0.04)	(0.45)	(0.35)	(0.39)	(6)	(6)	(9)
200	0.197	0.178	0.151	1.63	2.94	3.60	88	89	89
	(0.02)	(0.03)	(0.02)	(0.23)	(0.27)	(0.37)	(4)	(5)	(6)
400	0.179	0.173	0.146	1.48	2.76	3.45	90	91	90
	(0.04)	(0.02)	(0.02)	(0.31)	(0.41)	(0.29)	(3)	(5)	(7)
600	0.195	0.149	0.123	1.46	2.41	3.15	105	106	106
	(0.01)	(0.01)	(0.04)	(0.34)	(0.18)	(0.27)	(6)	(6)	(4)

Ginkgo densities were 8, 16, and 24 seedlings per m^2 respectively. Densities of rapeseed and broad bean were 0, 5, 8 and 12 seedlings per m^2. Wheat densities were 0, 200, 400, 600 seedlings per m^2. The numbers in brackets are standard errors of mean ($n = 3$)

strongest root competition for soil resource occurred between Ginkgo and rapeseed, Ginkgo and wheat second, and Ginkgo and broad bean the weakest.

Both Ginkgo density and crop density had a strong ($P < 0.01$) influence on total biomass of Ginkgo per unit land area in all three mixtures (Fig. 2a–c). Ginkgo total biomass per m^2 increased significantly with the increase of Ginkgo density. But as crop density increased, there was a significant reduction in Ginkgo biomass within each Ginkgo density. Mixtures had a marked influence on Ginkgo biomass per unit area ($P < 0.05$). Ginkgoes grown in Ginkgo/broad bean mixture had the highest biomass per m^2 of the three mixtures; Ginkgoes in the other two mixtures had approximately the same biomass production per unit area (Fig. 2).

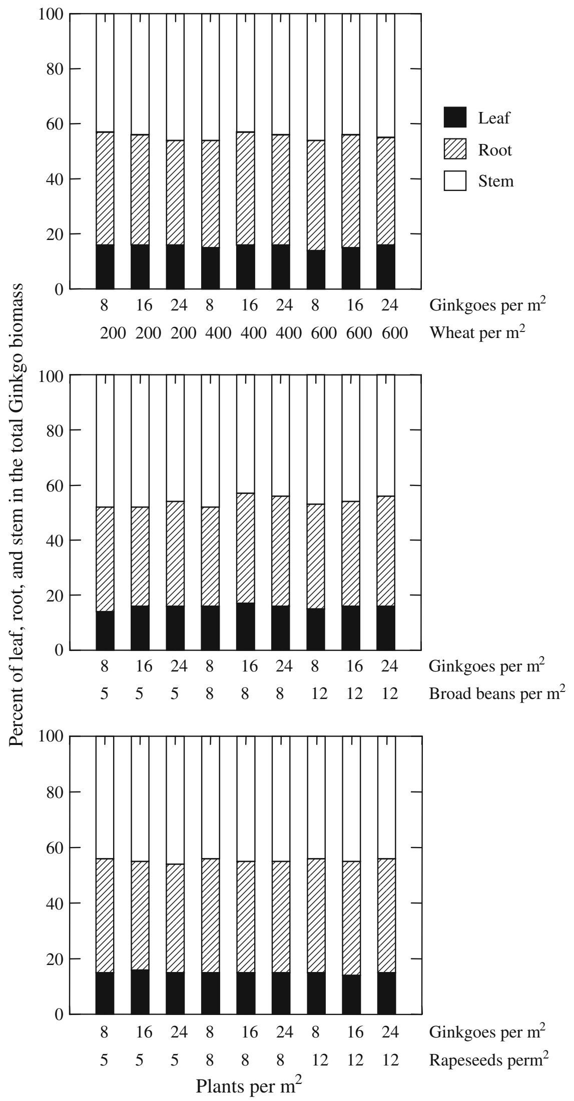

Fig. 1 Percent of leaf, root, and stem in the total Ginkgo biomass for each Ginkgo: crop ratio in the three mixtures (*top*: Ginkgo/wheat; middle: Ginkgo/broad bean; and *bottom*: Ginkgo/rapeseed) from the Taixing field factorial experiment

Crop biomass allocation—RSR

RSR of rapeseed decreased slightly with increasing crop density and increased very slightly with increasing Ginkgo density in the Ginkgo/rapeseed mixture (Fig. 3a). Both Ginkgo and crop density had a significant ($P < 0.001$) effect on RSR of wheat and broad bean. The RSR of wheat and broad bean decreased significantly as their own densities increased (Fig. 3b, c), but the ratio increased with increasing Ginkgo density, suggesting that there was strong above- and below-ground competition for light and soil resources between Ginkgo and the two crop species. Although neither Ginkgo nor crop density had a significant impact on rapeseed RSR in the Ginkgo/rapeseed mixture ($P = 0.658$), the change in RSR of rapeseed had a similar pattern as did wheat and broad bean. Compared with rapeseed, wheat and broad bean had larger RSR in mixtures with Ginkgo, indicating that wheat and broad bean mainly competed for soil nutrients. Therefore, each crop species showed different competition strategies for resources.

Relative importance of above- and below-ground competition

All RCI values are larger than zero (Table 4), implying that there exists above- and below-ground competition between Ginkgo and crop species. For the Ginkgo/rapeseed mixture, aboveground RCI declined as rapeseed density increased (Table 4). For the Ginkgo/wheat and Ginkgo/broad bean mixtures, however, aboveground RCI increased markedly as crop density increased. Mean aboveground RCI and belowground RCI values for all treatments for each mixture were 0.26 and 0.32 for Ginkgo/rapeseed, 0.29 and 0.26 for Ginkgo/broad bean, and 0.49 and 0.29 for Ginkgo/wheat (Table 4), respectively. The belowground RCI value increased significantly with increasing crop density and declined significantly with increased Ginkgo density ($P < 0.05$). Aboveground RCI had different response patterns to crop and Ginkgo density in the three mixtures. For one crop species, a higher RCI value means that it has a greater amount of competition. The RCI values here indicate that aboveground competition is weaker than belowground competition in the Ginkgo/rapeseed mixture, but aboveground competition is stronger than belowground competition in the Ginkgo/wheat and Ginkgo/broad bean mixtures.

Land equivalent ratio

LER values larger than one indicate an advantage from Ginkgo/crop mixtures in terms of the use of environmental resources for plant growth. LER values less than one indicates that resources are used more efficiently by monoculture crops than by intercrop mixtures. All LER values of shoot, root, and shoot plus

Table 3 Root/shoot ratios of four-year-old Ginkgoes for each Ginkgo: crop ratio in the three Ginkgo/crop mixtures in the Taixing field factorial experiment

Ginkgos per m^2	8	16	24	Mean
Ginkgo and rapeseed mixture				
Rapeseed per m^2				
5	0.63 (±0.015)	0.64 (±0.012)	0.68 (±0.021)	0.65
8	0.66 (±0.021)	0.66 (±0.024)	0.69 (±0.041)	0.67
12	0.69 (±0.018)	0.68 (±0.012)	0.68 (±0.015)	0.68
Mean	0.66	0.66	0.68	0.67*
Ginkgo and wheat mixture				
Wheat per m^2				
200	0.60 (±0.054)	0.68 (±0.011)	0.66 (±0.032)	0.65
400	0.64 (±0.022)	0.66 (±0.046)	0.68 (±0.044)	0.66
600	0.68 (±0.019)	0.63 (±0.051)	0.71 (±0.027)	0.68
Mean	0.64	0.66	0.69	0.66*
Ginkgo and broad been mixture				
Broad bean per m^2				
5	0.60 (±0.045)	0.56 (±0.017)	0.62 (±0.06)	0.60
8	0.56 (±0.046)	0.66 (±0.026)	0.66 (±0.034)	0.62
12	0.62 (±0.022)	0.620 (±0.019)	0.67 (±0.026)	0.64
Mean	0.591	0.61	0.64	0.62*

Numbers in brackets are standard deviations ($n = 3$). (Overall means for each mixture pooled from nine Ginkgo: crop ratios in each mixture are indicated by *)

root were more than one for all treatments with the exception for Ginkgo: broad bean ratio 8:8, Ginkgo: wheat ratios 8:200 and 16:200, and Ginkgo: rapeseed ratio 8:5. Overall mean shoot LER values pooled from all nine ratios in each mixture were larger than shoot plus root LER and root LER. The highest efficiency of land use (or the highest shoot plus root LER) in this trial was obtained for Ginkgo: broad bean ratio of 24:12 (LER = 1.30), Ginkgo: wheat ratio of 16:600 (LER = 1.38), and Ginkgo: rapeseed ratio of 24:12 (LER = 1.52) for shoot plus root LER values (Table 5).

Relative crowding coefficient for Ginkgo and for crop

Ginkgo density and crop density both had a significant ($P < 0.001$) influence on relative crowding coefficient for Ginkgo (RCCg) and for crop species (RCCc). RCCg and RCCc had the same response pattern in all three mixtures except when broad bean at the density of 5 plants per m^2). RCCg increased rapidly with increasing Ginkgo density; however, it decreased significantly as crop density increased, implying that increased Ginkgo density together with low crop density resulted in the highest RCCg values, (i.e., increased Ginkgo competitive ability). In contrast, RCCc decreased as Ginkgo density increased and increased as crop density increased. Mean RCCg and RCCc values show that crop species were more competitive than Ginkgo at low Ginkgo density (e.g., eight Ginkgo seedlings per m^2) but less competitive than Ginkgo at high Ginkgo density (e.g., 24 Ginkgo seedlings per m^2). Competitive ability of individual species in the Ginkgo/crop mixtures changed with varying Ginkgo and crop densities. Mean RCC for rapeseed was larger ($P = 0.035$) than the other two crop species (Table 6), meaning that rapeseed is more competitive than the other two crop species when they all mixed with Ginkgo.

Combined biomass yield of Ginkgo and crop species

There was a significant ($P < 0.05$) difference in combined component biomass per m^2 among different plant combinations (i.e., Ginkgo: crop ratios, see

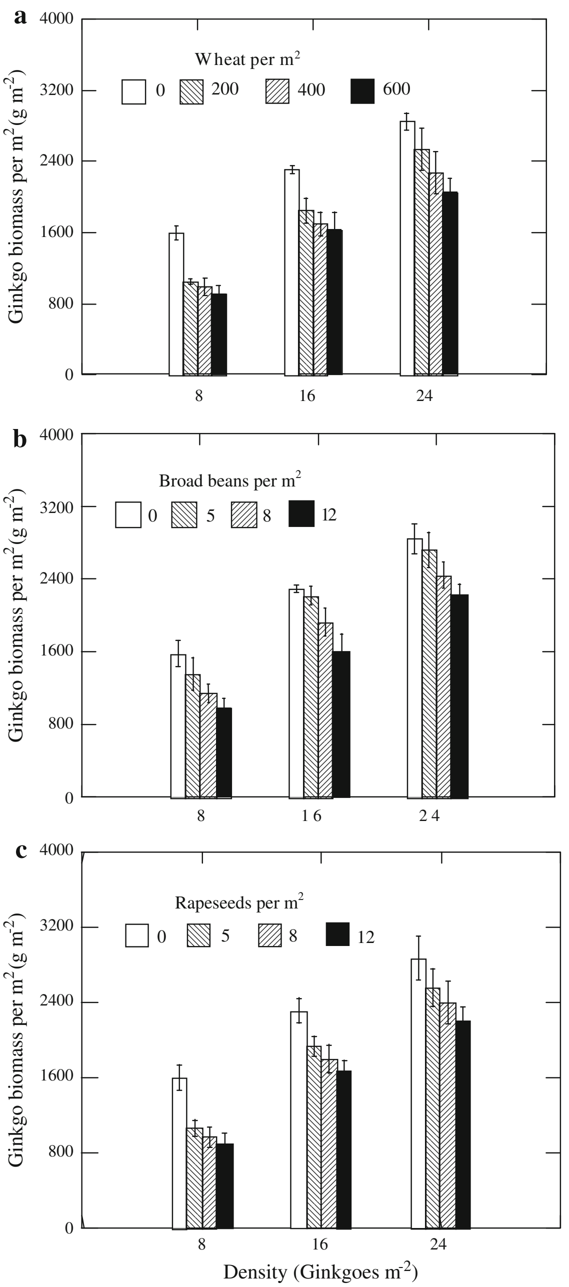

Fig. 2 Total biomass of four-year-old Ginkgoes per unit land area for each combination grown in the three mixtures (**a** Ginkgo/wheat; **b** Ginkgo/broad bean; and **c** Ginkgo/rapeseed) from the Taixing field factorial experiment. *Bars* represent mean ± 1 SE ($n = 3$)

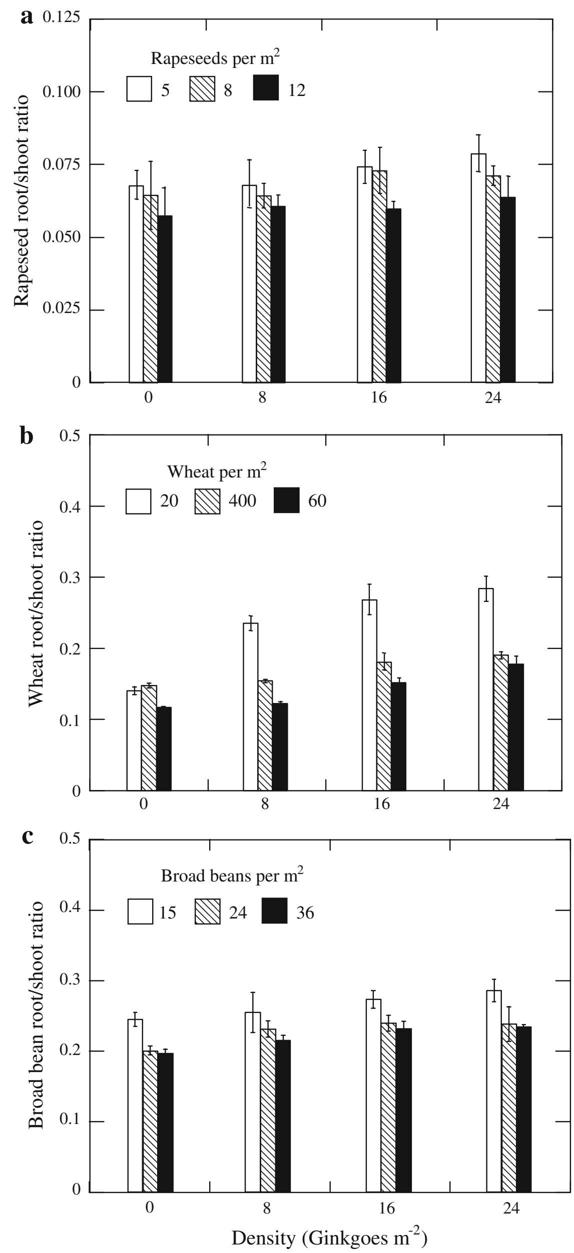

Fig. 3 Root (**a**), shoot (stem and leaf) (**b**), seed (**c**), and total biomass (**d**) per m^2 of wheat grown in the different Ginkgo/wheat combinations in the Ginkgo/wheat mixture from the Taixing field factorial experiment. *Bars* represent mean ± 1 SE ($n = 3$)

Fig. 4a, c, e). In the Ginkgo/rapeseed mixture, increased rapeseed density resulted in a significant increase in combined biomass per m^2 (Fig. 4a). However, increased broad been density caused a significant decrease in combined biomass per m^2 in Ginkgo/broad bean mixture (Fig. 4c), and a slight decrease at a density of 24 Ginkgoes per m^2 in the Ginkgo/wheat mixture (Fig. 4e). There was a

Table 4 Relative competition intensity (RCI) for aboveground and belowground for different Ginkgo/crop combinations growing in three Ginkgo/crop mixtures in the Taixing field factorial experiment

Gingkoes per m^2	Aboveground			Belowground		
	8	16	24	8	16	24
Ginkgo/rapeseed mixture						
Rapeseed per m^2						
5	0.70	0.23	0.32	0.35	0.26	0.20
8	0.20	0.21	0.20	0.47	0.26	0.21
12	0.18	0.16	0.14	0.57	0.30	0.21
	0.26*			0.32*		
Ginkgo/broad bean mixture						
Broad bean per m^2						
5	0.19	0.13	0.12	0.19	0.08	0.04
8	0.37	0.25	0.23	0.54	0.25	0.24
12	0.51	0.50	0.35	0.62	0.35	0.26
	0.29*			0.26*		
Ginkgo/wheat mixture						
Wheat per m^2						
200	0.54	0.46	0.19	0.22	0.15	0.04
400	0.58	0.58	0.29	0.52	0.19	0.17
600	0.70	0.67	0.38	0.68	0.38	0.23
	0.49*			0.29*		

Values with * means overall mean ($n = 3$)

Table 5 Land equivalent ratio (LER) values of shoot, root, and shoot plus root for Ginkgo/crop combinations in three mixtures from the Taixing field factorial experiments

Ginkgoes per m^2	Shoot LER			Root LER			Shoot plus root LER		
	8	16	24	8	16	24	8	16	24
Ginkgo/broad bean mixture									
Broad bean per m^2									
5	1.46	1.61	1.59	1.28	1.21	1.22	0.84	1.07	1.13
8	0.94	1.22	1.15	1.22	1.11	1.12	0.93	1.11	1.17
12	1.02	1.17	1.17	1.07	1.02	1.04	1.13	1.24	1.30
Overall mean	1.26			1.14			1.10		
Ginkgo/wheat mixture									
Wheat per m^2									
200	1.34	1.69	2.06	0.98	0.98	1.14	0.85	1.03	1.21
400	1.09	1.43	1.77	1.07	1.01	1.05	1.15	1.23	1.27
600	1.04	1.41	1.62	1.07	1.04	1.02	1.22	1.38	1.31
Overall mean	1.49			1.04			1.18		
Ginkgo/rapeseed mixture									
Rapeseed per m^2									
5	1.14	1.29	1.23	1.12	0.91	1.17	0.99	1.19	1.27
8	1.09	1.32	1.25	1.11	1.12	1.20	1.11	1.13	1.14
12	1.08	1.32	1.30	1.11	1.13	1.21	1.23	1.42	1.52
Overall mean	1.22			1.12			1.22		

Overall means of three kinds of LER were averaged from the nine combinations of the two plant species in each Ginkgo/crop mixture ($n = 3$)

Table 6 Relative crowding coefficient for Ginkgo (RCCg) and crop species (RCCc) for different plant combinations from three mixtures in the Taixing field factorial experiment

Ginkgoes per m^2	RCCg and RCCc					
	8		16		24	
Crop plants per m^2	Ginkgo (G) and wheat (W)					
Wheat	G	W	G	W	G	W
200	0.86	1.16	1.13	0.88	1.27	0.79
400	0.68	1.46	0.89	1.13	1.19	0.84
600	0.61	1.64	0.77	1.29	1.00	1.00
Mean	0.72	1.42	0.98	1.10	1.15	0.88
	Ginkgo (G) and broad bean (BB)					
Broad bean	G	B	G	B	G	B
5	0.88	1.13	1.50	1.00	1.38	0.82
8	0.86	1.16	1.08	0.94	1.25	0.85
12	0.73	1.68	0.94	1.32	1.14	0.88
Mean	0.82	1.32	1.17	1.09	1.26	0.85
	Ginkgo (G) and rapeseed (R)					
Rapeseed	G	R	G	R	G	R
5	0.76	1.32	1.01	0.99	1.22	0.82
8	0.65	1.53	0.87	1.15	1.01	0.99
12	0.57	1.74	0.75	1.37	0.84	1.20
Mean	0.66	1.53	0.88	1.19	1.02	1.00

$n = 3$

G Ginkgo, *W* wheat, *R* rapeseed, *B* broad bean

significant difference in the combined plant component biomass between the Ginkgo/rapeseed and the other two mixtures ($P < 0.05$); but there was no significant difference in combined biomass between Ginkgo/broad bean and Ginkgo/wheat mixtures (Fig. 4c, e). Among the three mixtures, the Ginkgo/rapeseed mixture had a much higher combined biomass than other two mixtures. The maximum combined biomass was about 4,800, 3,000, and 2,800 g per m^2 for Ginkgo: rapeseed ratio 24:12, Ginkgo:broad bean ratio 24:5, and Ginkgo: wheat ratio 24:200, respectively (Fig. 4a, c, e). There was a significant difference in combined economic yield (dry Ginkgo leaf mass and crop seeds) per m^{-2} among the three Ginkgo densities for all three mixtures ($P < 0.05$, Fig. 4b, d, f). The Ginkgo:rapeseed ratio 24:5, Ginkgo:broad bean ratio 24:5 and Ginkgo:wheat 24:200 ratio had the highest economic income for the respective mixtures. The Ginkgo/broad bean mixture had the best combined economic yield (Fig. 4d).

Vector competition analysis of the Ginkgo/crop mixtures

Response vectors for all other nine treatments (i.e., Ginkgo: crop ratios) are presented in Fig. 5. No antagonistic relationship (i.e. vector pointing to the left-lower quadrate of Fig. 5) was detected for Ginkgo and wheat, Ginkgo and broad bean mixtures (Fig. 5a, c). Only one Ginkgo and rapeseed mixture (8G5R) demonstrated antagonistic relationship (both Ginkgo and rapeseed biomass decreased from reference point). The results illustrate that the Ginkgo/wheat and Ginkgo/broad bean mixtures had a similar pattern and exhibited mainly compensatory competition (i.e. vectors pointing towards upper left and lower right quadrates) in which Ginkgo biomass production decreased while inducing favorable effects on wheat and broad bean. Relatively large synergistic effect (vectors pointing toward upper right quadrate) was demonstrated for four Gnikgo and broad bean

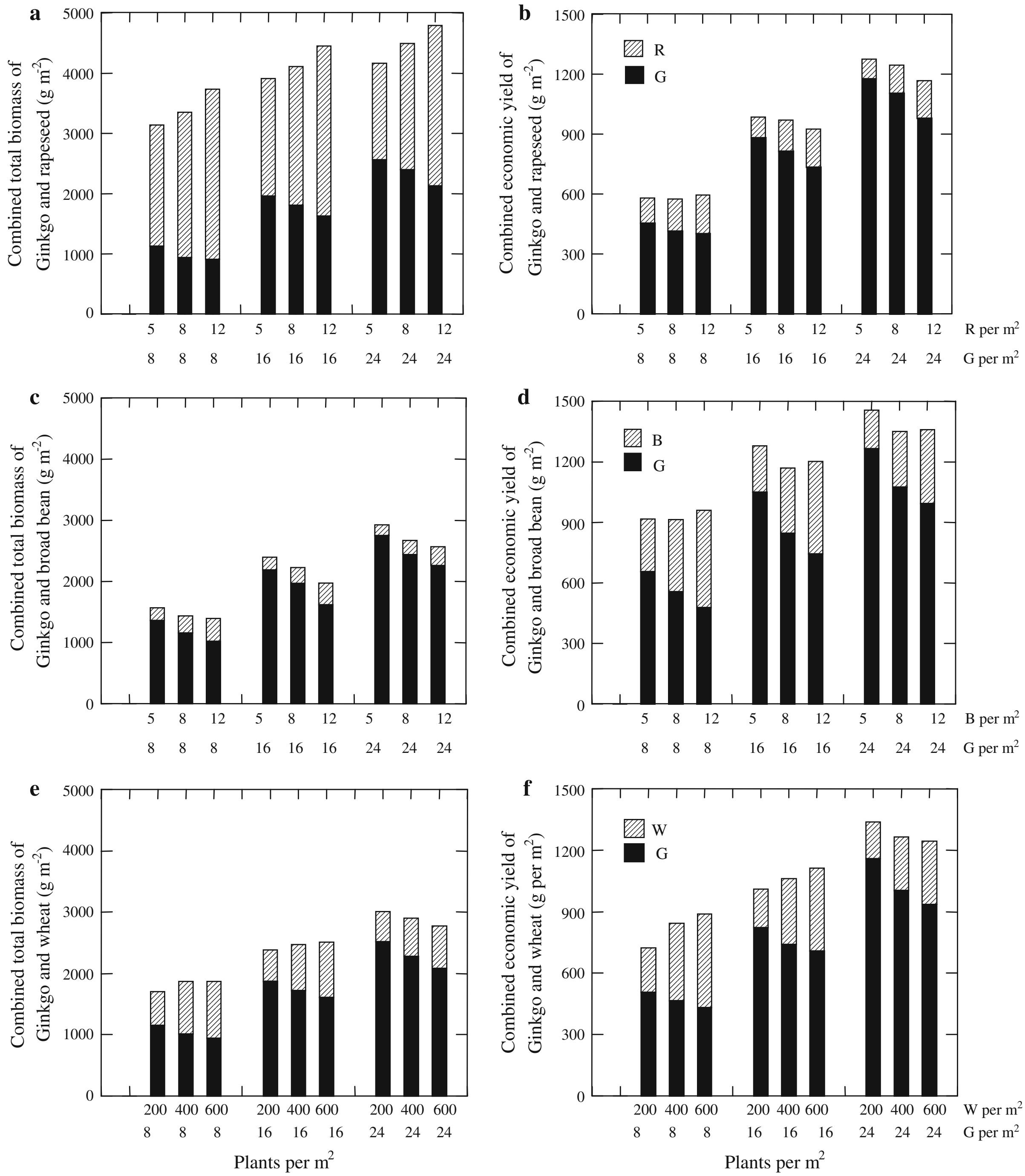

Fig. 4 Combined total biomass and economic yield (i.e., Ginkgo leaf and seed) pooled from three replicates of four-year-old Ginkgo and intercropped crop species growing in the three mixtures (**a** and **b** Ginkgo/rapeseed, **c** and **d** Ginkgo/broad bean, and **e** and **f** Ginkgo/wheat) from the Taixing field factorial experiment. Ginkgo *G*, wheat *W*, rapeseed *R*, and broad bean *B*

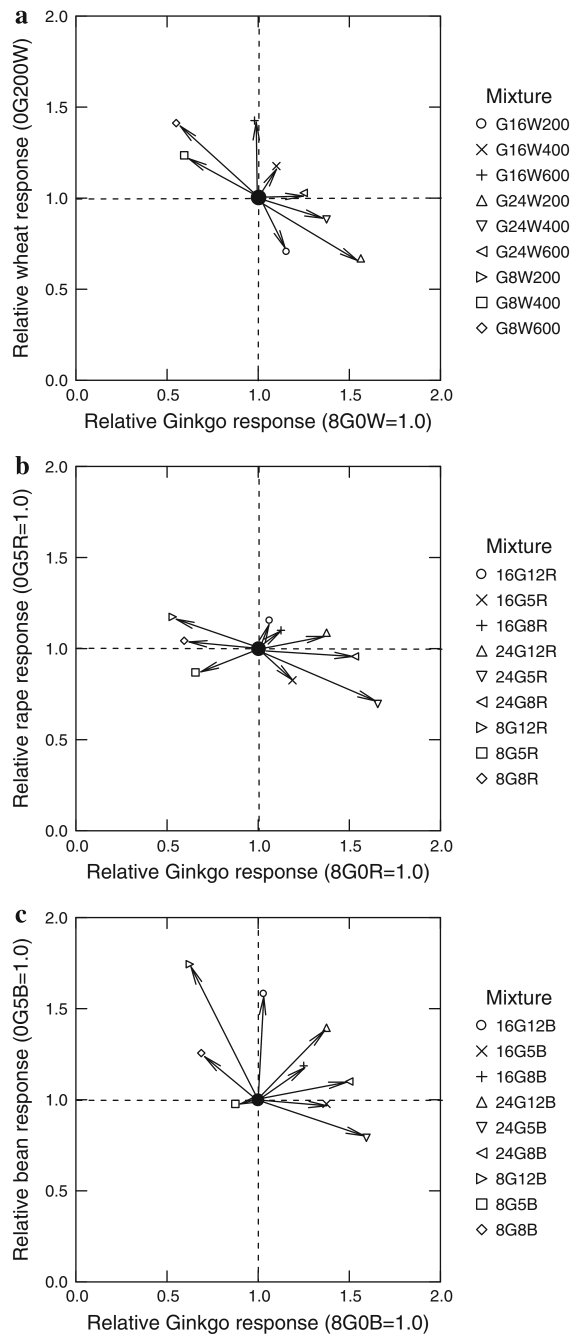

Fig. 5 Vector competition analysis diagrams of biomass in the Ginkgo/wheat (**a**), Ginkgo/rapeseed (**b**), and Ginkgo/broad bean (**c**) mixtures in the Taixing factorial experiments. The responses for Ginkgo pure culture 8G0W, 8G0R and 8G0B were standardized to 1.0. The responses for pure cultures of crop species 0G200W, 0G5R and 0G5B were standardized to 1.0 for comparison with the other mixtures

mixtures (16G12B, 24G12B, 16G8B and 24G8B in Fig. 5c).

Discussion

In the study we used factorial designs to explore the effects of Ginkgo/crop interference on growth, and yield at different levels of mixture. The results indicate that components of biomass production of Ginkgo are all sensitive to the presence and density change of the crop species. In the contrary wheat and broad bean were positively affected by increasing Ginkgo density. Rapeseed was negatively affected by increasing Ginkgo density. The mutual antagonistic effect for the Ginkgo/rapeseed mixture might be caused by the well-developed root and shoot systems (large below-ground and aboveground biomass) of rapeseed that competed strongly for soil resource.

Ginkgo leaf characteristics

One of the objectives of this study is to examine the effect of mixing crop species with Ginkgo on leaf characteristics such as LAS, SLA and LAI of Ginkgo because of economic value of Ginkgo leaf for flavonoid production. The results of LAS, SLA and LAI indicated that there were no differences among the three Ginkgo and crop species mixtures. However, increasing crop density significantly reduced LAS and LAI. Increasing Ginkgo density was the main reason for increased LAI. SLA was not affected by crop density mainly because of separation of temporal and spatial niche between Ginkgo and crop species in terms of phenology and individual heights.

Competitive ability

Our results of this study support that RCC changes with different total densities reported by Firbank and Watkinson (1985a, b) and Connolly (1987), For instance, RCC for Ginkgo seedlings was higher than that for crop plants at high Ginkgo densities, whereas the reverse was true at low Ginkgo densities. In other words, crop species were stronger competitors than Ginkgo at low Ginkgo density, but Ginkgoes were stronger competitors than the three crop species at high Ginkgo densities. When the mean RCCg and RCCc pooled from all plant component combinations in each mixture were considered, the three crop species generally had higher RCC values than Ginkgo, suggesting that the three crop species were more competitive than Ginkgo. At each Ginkgo density, an increase of crop density resulted in a significant decline in RCC for Ginkgoes but an increase in RCC for crop plants; increased crop density reduced Ginkgo's competitive ability.

Relative importance of below- and above-ground competition

Our results indicate that mean root RCI values were larger than shoot RCI in Ginkgo/rapeseed mixture, inferring that belowground competition between Ginkgo and rapeseed was more intense than aboveground competition. However, mean shoot RCI in Ginkgo/broad bean and Ginkgo/wheat mixtures were higher than root RCI, meaning that aboveground competition was more intense than belowground competition. Several possibilities might be responsible for the difference in shoot RCI and root RCI values: (1) Ginkgo bud burst and foliage development commenced in early April and foliage was fully developed in early May. Rapeseed completes its flowering in late March, seed filling in April, and seed's maturation in early May. It was harvested in mid- or late-May. Therefore, belowground competition for soil resource is more intense than aboveground competition; (2) Field observation made in late May 2001 showed that mean height of Ginkgo and the three crop species differed significantly, being 120 cm for Ginkgo, 160 cm for rapeseed, 55 cm for broad bean, and 75 cm for wheat in the field factorial experiments, respectively. Rapeseed seriously shaded Ginkgo seedlings. To keep aboveground optimum growth, rapeseed allocated more carbohydrates to and developed its root system; and (3) the rapeseed had a much larger root system and higher root biomass than the other two crop species. This evidence may be interpreted to indicate that belowground competition was stronger than aboveground competition for the Ginkgo/rapeseed mixture, but aboveground competition was stronger than belowground competition for the Ginkgo/wheat and Ginkgo/broad bean mixtures.

Land equivalent ratio

Results of this study show that LER values of shoot, root, and root plus shoot for most Ginkgo: crop ratio treatments were larger than one, implying that appropriately designed Ginkgo/crop intercropping systems have biomass advantages over monocultures. In all three Ginkgo/crop mixtures, the mean aboveground LER values were larger than belowground LER inferring that aboveground niche differentiation was more than that of belowground. All these difference may be attributed to an increased aboveground and belowground space and temporal niche differentiation during the growing season because of mixing.

Vector competition analysis

The results showed that one Ginkgo: rapeseed combination (8G5R) exhibited an antagonism interaction type, while two of the other mixture ratios showed a compensatory interaction. It suggests that the only antagonistic Ginkgo: rapeseed combination is not suitable for intercropping systems; all other combinations in the three mixtures are feasible for Ginkgo/crop intercropping. Major compensatory and synergistic effects were detected for 8 out of all 9 Ginkgo/broad bean mixtures. It is likely attributed to the nitrogen fix ability of broad bean. All 9 Ginkgo/wheat combinations had compensatory and synergistic relationship. This is mainly due to temporal niche separation because wheat was planted on November when Ginkgo is leafless and harvested in mid-June next year.

Optimum Ginkgo/crop combinations

In a tree-crop intercropping system, competition between plant components for growth factors like light, water, nitrogen and minerals has a decisive influence in the productivity of the system. Plants compete with each other for the available resources, with each plant trying to fulfill its needs. Biomass production is approximately linearly related to the uptake of the resource that limits growth, so that the distribution of the limiting resource among the plants is reflected in their biomass. Grime (1979) and Wilson and Keddy (1986) pointed out that biomass might be a very good indicator of long-term photosynthetic efficiency because it reflects the production of dry matter over long periods of time and integrates the effects of varying environmental factors. However, growth and competitive ability of a plant depend ultimately on its integrated lifetime carbon balance, which is associated with construction and maintenance costs. Spitters

(1983) concluded that interplant competition is better measured by biomass than by photosynthetic rate or yield of any plant part, because dry-matter distribution within the plant varies with the competitive stress. For this reason, total biomass in a Ginkgo/crop system is one of the key parameters by which to evaluate the intercropping system productivity.

In Jiangsu Province, farmers usually grow Ginkgoes for leaf-harvesting starting from seeds; and hence leaf production per unit area (economic yield) is of priority for them to decide whether a Ginkgo/crop mixture can be employed or not. The second consideration for farmers is that Ginkgo leaves should have high flavonoid yield to obtain a high economic income. Our study shows that Ginkgo: rapeseed (or broad bean) ratio 24:5 and Ginkgo: wheat ratio 24:200 in respective Ginkgo/crop mixtures had maximum economic yield (yield of Ginkgo leaves and crop seeds). Because the Ginkgo/broad bean mixture had higher monetary income than the other two mixtures, Ginkgo: broad bean at a ratio of 24:5 is recommended to farmers for intercropping management in northern Jiangsu province, China.

Although our experiment was lasted only for two years farmers in agroforestry practice in Jiangsu Province will continue the Ginkgo and crop mixture by pruning Ginkgo to keep it in certain height for easy harvesting of leaves and rotate different crop species like wheat, rapeseed and broad bean based on short term market value fluctuation. In long term we need to study the effects of different mixtures on soil fertility to help establish sustainable agroforestry system.

Conclusions

The results presented in this paper support the alternative hypotheses that: (1) there is a mixture and component species effect on morphological, and growth characters such as LAS, mass production and carbon allocation; (2) the competitive ability of component species in the three Ginkgo/crop mixtures differs, and is affected by planting density; and (3) Mixtures can achieve a higher combined mass production than pure Ginkgo stands and pure crop system. The main conclusions are:

1. With increasing Ginkgo density, LAS and Ginkgo biomass per seedling decreased and LAI and biomass per unit land area increased significantly. LAS, LAA, and biomass per unit area of Ginkgo decreased and Ginkgo's SLA increased substantially as crop density increased. Components of crop biomass per unit land area increased with increased crop density and decreased with increased Ginkgo density. The root/shoot ratio of the three crop species decreased as crop density increased and increased as Ginkgo density increased.
2. Root RCI values were larger than shoot RCI in the Ginkgo/rapeseed mixture, suggesting that root competition was more intense than shoot competition in the Ginkgo/rapeseed mixture. Majority of shoot RCI values in the Ginkgo/broad bean and Ginkgo/wheat mixture were higher than root RCI. Thus, shoot competition in the Ginkgo/wheat and Ginkgo/broad bean mixtures was more intense than root competition.
3. Increasing Ginkgo and crop density resulted in a respective increase in RCCg and RCCc. Mean RCCg and RCCc values indicated that the crop species were more competitive than Ginkgo at low Ginkgo density, but less competitive than Ginkgo at high Ginkgo density. Both RCCg and RCCc changed as a function of density of Gingko and crop species. Analysis of the balance of within- and between-species influences showed that rapeseed and broad bean were superior competitors, but wheat was less competitive than Ginkgo in mixture. Vector competition analysis suggested that there existed an antagonistic interaction between Ginkgo and rapeseed. The integration of all the parameters describing competitive ability of plant species showed that among the three crop species, rapeseed was more competitive than the other two crop species.
4. Overall mean shoot LER values were the larger than mean shoot plus root LER and mean root LER. The highest efficiency of land use (i.e., the highest shoot plus root LER) was obtained for Ginkgo: wheat ratio of 16:600, Ginkgo: broad bean ratio of 24:12, and Ginkgo: rapeseed ratio of 24:12. LER values larger than one showed that plant growth factors were used more efficiently by the intercrop than by monoculture crops. Therefore, combined biomass production of the component plant species was significantly greater in

the Ginkgo/crop mixtures than in monocultures crops (Ginkgo, broad bean, wheat, and rapeseed).

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