Author Bio: M.K. Bomford is Principal Investigator and Extension Specialist in organic and sustainable vegetable production with the Kentucky State University Land Grant Program, 400 East Main Street, Frankfort, KY 40601 (E-mail: michael.bomford@kysu.edu; Web: http://organic.kysu.edu). This article draws on data collected for the author's PhD dissertation at West Virginia University. The author extends sincere thanks to committee members William Bryan, Linda Butler, Herbert Cole, James Kotcon, and Sven Verlinden for assistance, support and advice. Research was supported by Hatch funds awarded to West Virginia University's Davis College of Agriculture.

Do tomatoes love basil but hate Brussels sprouts? Competition and land-use efficiency of popularly recommended and discouraged crop mixtures in biointensive agriculture systems

M.K. Bomford

Biointensive agriculture (BIA) is a suite of small-scale agricultural practices that include the use of high-density mixed plantings. It has been promoted to gardeners and resource-limited farmers as a sustainable organic vegetable production method that makes efficient use of land, water, and other resources. Certain crop mixtures are popularly recommended for use in BIA systems (e.g. tomato, *Lycopersicon esculentum* Mill., and basil, *Osimum basilicum* L.); others are discouraged (e.g. tomato and Brussels sprout, *Brassica oleracea* L.). Rain-fed BIA gardens were planted in 2001 and 2002 to compare land-use efficiency of pure stands and two-crop mixtures of tomato, basil, and Brussels sprout. Brussels sprout was the most competitive crop among the three tested, accounting for at least two-thirds of the land equivalence ratio (LER) in mixtures; basil was the least competitive component crop, accounting for less than one-third of LER. Mixtures made more efficient use of land than pure stands only in 2002, which was hotter and drier than 2001. Potential land-use efficiency of mixtures was likely underestimated in both years because the method commonly recommended for calculating inter-plant spacing in BIA mixtures tends to result in lower total density in mixtures than in segregated pure stands, and does not account for different mixture proportions. New recommendations are proposed to address these problems, and are incorporated into a companion planting spacing calculator available for download. Marketable Brussels sprout yield was poor because of excessive heat for the cool-season crop, not because of poor plant growth. The popularly recommended mixtures did not make more efficient use of land than the popularly discouraged mixture.

biointensive agriculture (BIA), companion planting, gardens, land equivalence ratio (LER), mixed cropping, relative competition intensity (RCI), resource use efficiency, resource-limited farms, small farms, soil plant analysis development (SPAD) index

INTRODUCTION

Biointensive agriculture (BIA) is a suite of land-intensive small-scale agricultural practices that include the use of high density mixed plantings grown in offset rows in deeply cultivated beds fertilized with compost (Jeavons 2006). BIA is promoted as a sustainable organic vegetable production method that makes efficient use of land, water, and other resources (Jeavons 2006). Few peer-reviewed studies have been published in response to calls for formal academic analysis of BIA systems (Jeavons 2001, Medvecky

2006), but broad interest in BIA is demonstrated by sales of more than 500,000 copies of a popular manual in its seventh edition (Jeavons 2006), by adoption of BIA by small-scale farmers in 130 countries around the world, and by a variety of papers presented at recent symposia (Miles *et al.* 2002, Doran et al. 2006, Omondi et al. 2006, Pia 2006, Mbugwa et al. 2006, Beeby et al. 2006, Bouyouris et al. 2006).

BIA systems use mixed plantings to increase land use efficiency (Jeavons 2006). Mixed plantings have been well-studied (e.g. Brown et al. 1985, Hart 1986, Theunissen 1997), and found to make more efficient use of land (Jolliffe 1997) and water (Kanton and Dennett 2004) than pure stands. According to the ecological concept of niche differentiation, mixtures are more productive than pure stands when mixing replaces stronger within-species competition with weaker between-species competition (Willey 1979, Vandermeer 1989, Jolliffe and Wanjau 1999). Since the choice of crops used in a mixture presumably has some effect on whether, or not, this occurs, certain crop combinations might be expected to consistently offer yield advantages over pure stands. Using the language of human relationships metaphorically, BIA manuals typically recommend specific crop combinations as beneficial "companions," and discourage others as "antagonists" (Riotte 1975, Jeavons 2006). For example, basil (*Osimum basilicum* L.) mixed with tomato (*Lycopersicon esculentum* Mill.) is said to improve tomato growth, but brassicas, such as Brussels sprout (*Brassica olerecia* L. var. capitata), are considered antagonistic to tomato; brassicas are said to benefit from mixing with aromatic herbs. In the language of Riotte (1975), tomatoes love basil but hate Brussels sprouts. The reputed effects of mixing certain plant species are frequently vague (e.g. "tomatoes and all members of the brassica family repel each other," Riotte 1975), and the rationale for these recommendations is often unclear: They are based on gardener experience and on laboratory assays involving the analysis of crystal formations produced by evaporating aqueous mixtures of plant extracts and copper chloride (Pfeiffer 1931, Riotte 1975). Although these assays show similar results when interpreted by blind panels or image analysis software (Andersen et al. 1999), a plausible mechanistic explanation of the relationship between copper chloride crystal formation and plant compatibility has not been proposed or tested. This may contribute to the fact that companion planting recommendations continue to be widely-circulated in the popular press, but largely untested in the horticultural literature.

A few studies published in the entomological literature report tests of specific mixtures recommended as companions in BIA manuals for their supposed ability to deter insect pests (Finch et al. 2003, Held et al. 2003). While a large body of literature supports the idea that crop diversity reduces arthropod pest pressure (Andow 1991, Smith and McSorely 2000) specific combinations recommended for BIA systems have not yet shown greater benefits than other mixtures.

Certain BIA practices may not be appropriate for some environments. According to Jeavons (2006), on well-structured soils the practice of 'double digging' -- deep cultivation with a spading fork -- "is not needed to maintain significant yields and may even deplete the quality of the [soil] structure." Indeed, the only published peer-reviewed study of double digging was conducted in well-drained, fertile soil with sufficient rainfall, and found that the practice offered no yield benefit (Holt and Smith 1998). A more recent preliminary study reached a similar conclusion, leading to call for factorial studies to evaluate the effect of individual BIA practices in different environments based on the concern that "promoting such a highly labor constraining practice as an integral part of the BIA package could preclude farmers from adopting the other, potentially more useful BIA components (i.e. compost use and close spacing of plants)" (Medvecky 2006). Some research suggests that the yield advantage associated with mixed planting is most pronounced under resource-limiting conditions, such as low moisture availability (Rao and Willey 1980, Natarajan and Willey 1986).

Nonetheless, BIA is promoted as an integrated package, based on an expectation of synergism between system components. Jeavons (2006) warns of possible soil depletion if some components are excluded from BIA systems. In emphasizing the need for cropping systems research recognizing the potential for synergism, Drinkwater (2002) calls for both whole-system comparisons and factorial experiments to address mechanistic hypotheses. While there is certainly a need for studies comparing BIA systems to other vegetable production systems, factorial studies are also necessary to determine which components of BIA systems are beneficial under a variety of sites and environments.

This study was conducted to compare BIA beds dedicated to pure stands to BIA beds growing popularly recommended mixtures (tomato and basil; Brussels sprout and basil), or a popularly discouraged mixture (tomato and Brussels sprout).

MATERIALS AND METHODS

Tomato (*L. esculentum* cv. 'WV-63'), basil (*O. basilicum* cv. 'Nufar') and Brussels sprout (*B. olerecia* var. gemmifera cv. 'Long Island') were grown in pure stands and as two-crop mixtures using BIA practices in 2001 and 2002.

Site preparation. Four replicated BIA gardens (61 m^2) of six beds were prepared on a south-facing slope (<4 % grade) on land in transition to organic production (West Virginia University Horticulture Farm, Morgantown WV, certified by Ohio Ecological Food and Farming Association, 2003). Soils were clay loams in the Dormont and Guernsey series that had grown mixed sod for several years before the study. Compost made from dairy manure and leaf much was applied in May of both years at 30 t ha^{-1} fresh weight (120, 78 and 140 kg ha^{-1} N, P and K, respectively, based on compost analysis) and incorporated by 'double digging' with a spading fork to a depth of 0.4 m (Jeavons 2006). Gardens were seeded to hairy vetch (*Vicia villosa* Roth) and winter rye (*Secale cereale* L.) following the final harvest in October 2001. The cover crop was killed by mowing before compost application in 2002.

Treatments. One of six treatments was randomly assigned to each bed in each garden (Table 1): Pure stand beds contained basil (BAS), Brussels sprout (SPT), or tomato (TOM); mixed beds contained tomato and basil (T&B), tomato and Brussels sprout (T&S), or Brussels sprout and basil (S&B). Thirty-five greenhouse-grown plants were transplanted by hand into each bed, in five offset rows of seven (Figure 1). Plant seeding, transplant, and harvest dates are shown in Figure 2. Interplant spacing was constant within and between rows. Interplant spacing in mixed plantings was the mean of component monoculture spacing (Table 1, after Jeavons 2006). The primary species, defined as the crop with the greater interplant spacing in monoculture, was every other plant in the first, third, and fifth rows of mixed beds (12 plants per bed); the secondary species was grown in the remaining spaces (23 plants per bed). Plant spacing determined bed area, which varied by treatment (Table 1, Figure 1). Treatments were re-randomized before planting in 2002.

Table 1. Treatments, bed areas, plant spacing, and plant densities used in this study (after Jeavons 2006).

				Density (plants m^{-2})		
Treatment	Code	Bed area (m^2)	Interplant spacing (cm)	Primary crop	Secondary crop	Overall
1. Basil – pure stand	BAS	2.5	30*	13.8	-	13.8
2. Brussels sprout – pure stand	SPT	6.0	46	5.9	-	5.9
3. Tomato – pure stand	TOM	7.9	53	4.4	-	4.4
4. Tomato and basil	T&B	4.8	41.5	2.2	4.5	7.2
5. Tomato and Brussels sprout	T&S	6.9	49.5	1.6	3.1	5.1
6. Brussels sprout and basil	S&B	4.1	38	2.7	5.3	8.6

*Jeavons (2006) recommends 15 cm spacing for basil. The 30 cm spacing used in these tests reflects other recommendations (Bradley and Ellis 1992, Gao and Bergefurd 1999, seed packet instructions).

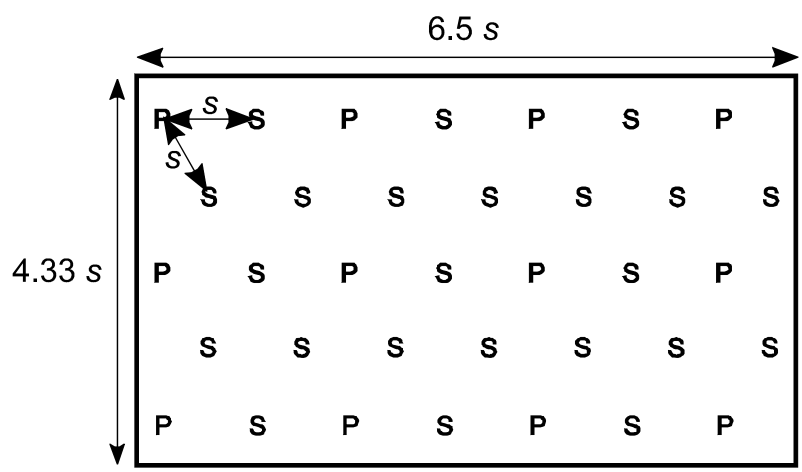

Figure 1. Mixtures consisted of a primary and secondary crop (P and S, respectively); the primary crop was the one requiring the greater plant spacing in monoculture (c.f. Table 1). Each plot had 35 plants. Mixed plots had 12 plants from the primary crop and 23 from the secondary crop. Plant spacing in mixtures (*s*) was the mean of the spacing used for each crop in monoculture. Bed dimensions were a function of plant spacing.

Resource availability and use. Plots were rain-fed. Precipitation and minimum and maximum temperatures were recorded daily at the Morgantown municipal airport, approximately 1 km from the study site. Degree days were calculated from 1 June using the single sine method and a 10 °C minimum cutoff (UC IPM online 2007). Tomato vines were suckered to leave a single dominant stem, which was staked and tied. Plots were kept weed-free by regular hand weeding. Canopy light penetration was measured by Sunfleck Ceptometer (Decagon, Pullman WA) between 1000 and 1500 h on three cloudless days in each year (Figure 2). Eight readings were taken at soil level in each bed. The upright meter was rotated 45° with each reading, to eliminate effects due to row orientation. Each reading recorded the proportion of a 1 m probe exposed to direct sunlight (Sunfleck proportion). The mean of all eight readings was used as the sample reading for a plot.

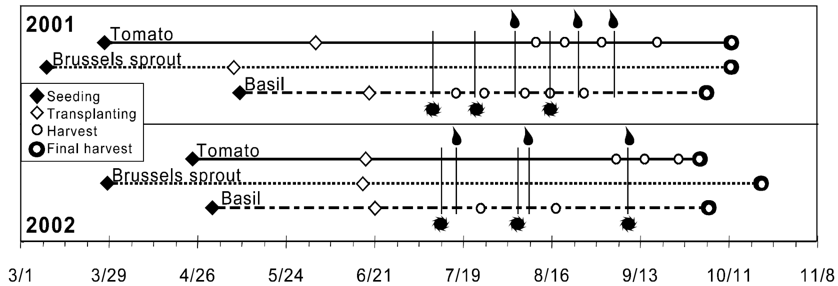

Figure 2. Temporal overlap of companion crops in 2001 (top) and 2002 (bottom). Markers show dates of seeding in the greenhouse (◆), transplanting to treatment plots (◇), harvest (○), and final harvest (⦿). Vertical lines show dates of soil moisture (♦) and canopy light penetration (✹) readings.

Soil volumetric water content (VWC) was measured in the top 20 cm using a HydroSense Soil Moisture Meter (Spectrum Technologies, Plainfield IL) on three days in the latter portion of each growing season (Figure 2). Readings were taken between plants, 50 cm from the east end of the second and fourth row of each bed. Readings were also taken 50 cm from the west end of the same rows, and in the center of each bed, in 2002 only. The mean of all readings taken in a plot was used as the sample value for that plot.

Relative chlorophyll content was measured with a portable chlorophyll meter (SPAD-502, Minolta Camera Co., Osaka, Japan) at final harvest. The meter measures transmission through a leaf of red light at a wavelength absorbed by chlorophyll (650 nm) and infra-red light at a wavelength not absorbed by chlorophyll (940 nm). It computes a Soil Plant Analysis Development (SPAD) value that estimates relative leaf chlorophyll content based on the ratio of these two values (Watanabe et al. 1980). One SPAD reading was taken from a fully-expanded leaf at the top of each plant, and the mean of all readings in a plot was used as the value for that plot.

Harvest. Tomatoes were harvested five times in 2001 and four times in 2002 (Figure 2). All fruits past the breaker stage were collected at each harvest, counted, and weighed. All aboveground biomass was collected at the final harvest. Ripe tomatoes, green tomatoes, and vines were sorted and weighed separately.

Basil was harvested six times in 2001 and three times in 2002 (Figure 1). All biomass more than 15 cm above the ground was collected and weighed at each harvest. All aboveground biomass was collected at the final harvest. Leaves and stems were weighed separately.

Brussels sprouts were harvested once at the end of each season (Figure 1). All aboveground biomass was collected. Marketable sprouts were counted and weighed separately from leaves and stems.

Analysis. One replicate was excluded from the analysis in 2001 because of severe groundhog (*Marmota momax* L.) damage to the Brussels sprouts. Total aboveground fresh weight collected from each crop was divided by the number of plants representing that crop in a bed to give the average aboveground plant biomass in mixtures and pure stands (P_{mix} and P_{mono}, respectively). Total aboveground fresh weight of each crop in each treatment was divided by bed area to give mixture yield, Y_{mix}, or pure stand yield, Y_{mono}. Analysis of variance (ANOVA) was used to analyze the logarithm of biomass per plant and yield for each crop by year (SAS Institute 2001). The ANOVA model was a randomized complete block with three treatments (pure stand and two mixtures) for each crop. Means were separated by Tukey's test when significant treatment effects were found.

Relative competition intensity (RCI) was calculated separately for each crop, replicate, and year according to Grace (1995):

$$RCI = \frac{P_{mono} - P_{mix}}{P_{mono}} \qquad \text{Eq. 1}$$

Relative yield (RY) was calculated by dividing the yield of a single crop in each mixed planting by its yield in a pure stand (Y_{mix}/Y_{mono}) (de Wit 1960). The land equivalence ratio (LER) for each mixture was calculated as the sum of both crops' RY (Willey and Osiru 1972).

The LER values of the intercrop treatments were tested for significance following methods recommended by Oyejola and Mead (1982). LERs were calculated separately for each replicate using the replicate plant yield for the numerators and the mean of pure stand yield across all replicates for the denominators. The LER values were then compared to a value of one by one-tailed t-test. This method tends to underestimate the true value of LERs by eliminating the variation in the ratio which is due to variability in pure stand yields, but it is statistically preferable to using the individual pure stand yield values for each replicate (Oyejola and Mead 1982, Vandermeer 1989).

RESULTS

Resource availability and competition. 2002 was hotter and drier than 2001 (Figure 3). Availability and use of two fundamental resources, light and water, was indicated by the proportion of the soil surface exposed to direct sunlight (Sunfleck) and the volumetric water content in the top 20 cm of soil (VWC), which were correlated in 2002 (r = 0.91, d.f. = 6, P = 0.01) but not 2001 (Figure 4). The variation in Sunfleck readings between treatments was lower in 2002 than in 2001, but variation in VWC was greater in 2002 (Figure 4). The relative order of treatments was similar between years. The least competition for sunlight occurred in the BAS and T&B plots; the most competition occurred in plots with Brussels sprout plants. More light penetrated the T&B mixture than the T&S mixture in both years; the difference between T&B and S&B was also significant in 2001.

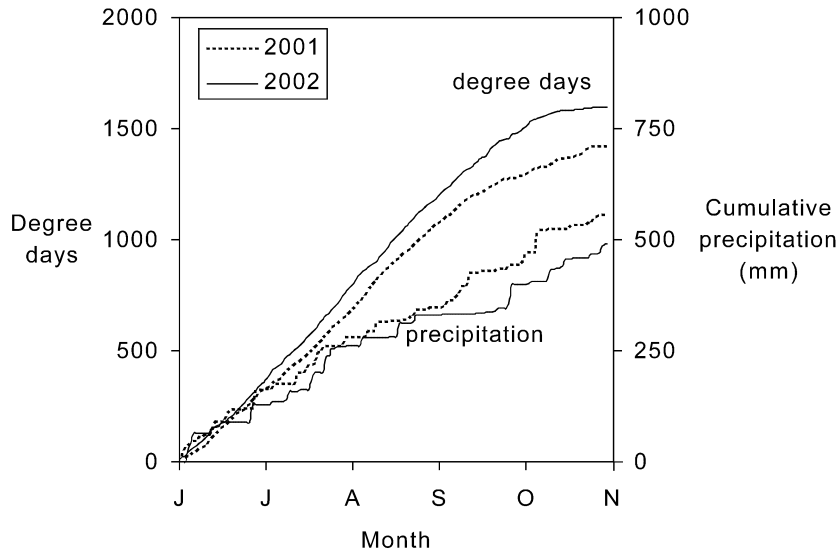

Figure 3. Cumulative degree days and precipitation between 1 June and 31 October, 2001 (dashed lines) and 2002 (solid lines). Degree days calculated in metric using the single sine method with a 10 °C cutoff.

The RCI in mixtures was always positive for one crop and negative for the other (Figure 5), meaning that one crop faced less competition in the mixture than in pure stands, and the other faced more. Brussels sprout plants faced less competition in mixtures than in pure stands; basil faced more competition in mixtures; and tomato faced more competition when paired with Brussels sprout, but less when paired with basil (Figure 5). The sum of RCIs for both crops in a mixture tended to be positive in 2001, but negative in 2002 (Figure 5), suggesting that net inter-specific competition was less than net intra-specific competition in 2002 only.

Basil. Basil yields averaged 1.4 and 3.4 kg m^{-2} in 2001 and 2002, respectively. The contribution of differing resource levels to this difference was confounded with the effect of reduced harvest frequency, allowing the basil canopy to fill in more in 2002 than in 2001 (Figure 4). Individual basil plants yielded more in pure stands than in beds with Brussels sprout companions (Table 2). Basil plants with tomato companions produced less biomass than plants in monoculture in 2001, but differences were not significant in 2002 (Table 2). Basil yields were five times greater in pure stands than in mixed plantings (Table 2).

Relative basil leaf chlorophyll content, measured in SPAD units at season end, was correlated with basil plant weight at final harvest when years were pooled (r = 0.91, d.f. = 20, P<0.001) and when data from 2001 (r = 0.90, d.f .= 8, P<0.001) and 2002 (r = 0.82, d.f.=11, P<0.002) were analyzed independently (Figure 6). Relative leaf chlorophyll content and basil yield were both higher in 2002 than in 2001. In both years the highest values were found in pure stands and the lowest were found in Brussels sprout mixtures (Figure 6).

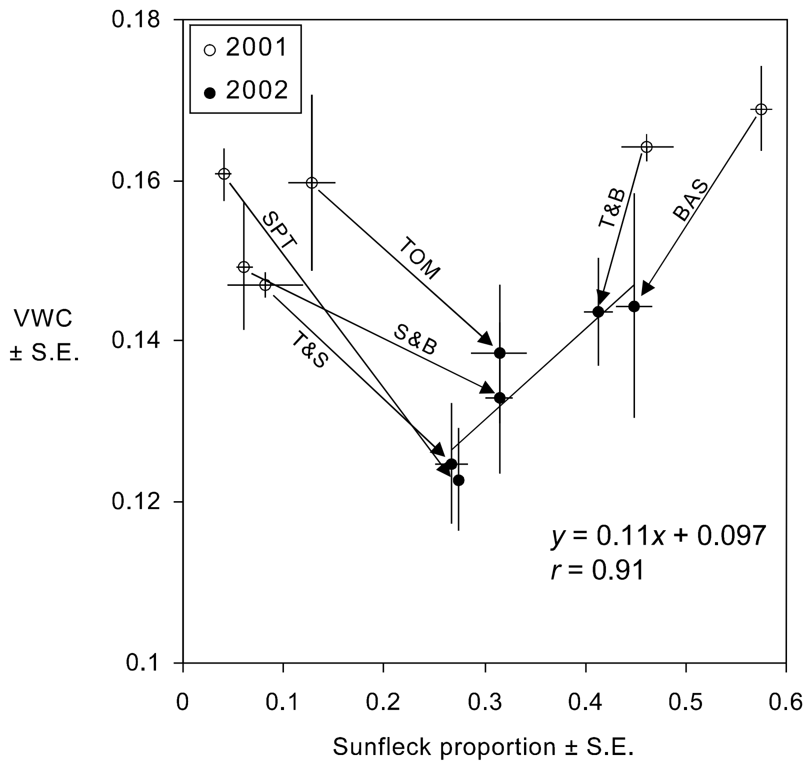

Figure 4. Proportion of soil surface exposed to sunlight (Sunfleck) and soil volumetric water content (VWC) by treatment in 2001 (○, *n* = 3) and 2002 (●, *n* = 4). Arrows show change between years. Bars denote standard error of each mean. Trendline and equation show relationship between Sunfleck and VWC in 2002; no significant relationship was found in 2001.

Brussels sprout. Aboveground Brussels sprout biomass removed at season end averaged 9.5 and 5.5 kg m^{-2} in 2001 and 2002, respectively. The marketable proportion of this biomass was very low because most auxiliary buds (sprouts) did not reach a marketable size, or were too loose. Marketable sprout weight in 2001 averaged 6.6% of plant biomass, resulting in a linear correlation ($r^2 = 0.44$, $n = 147$, $P < 0.001$) between the two quantities. Marketable weight in 2002 was < 0.3% of plant biomass.

Brussels sprout plants grown with basil tended to be heavier than those grown in monoculture (Table 2), but this difference was only statistically significant in 2002 (Table 2). Yield did not differ by treatment (Table 2). No relationship was observed between relative leaf chlorophyll content and Brussels sprout yield (data not shown).

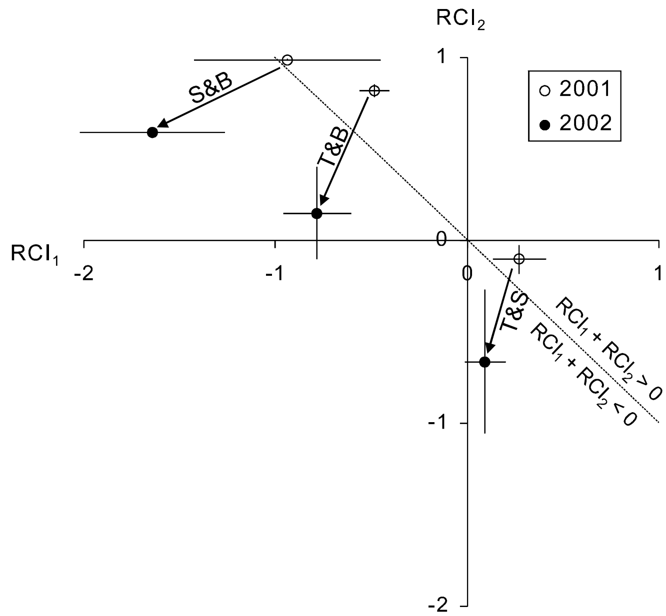

Figure 5. Relative Competition Intensity (RCI) for plants representing primary and secondary crops (RCI_1 and RCI_2, respectively) in each mixture in 2001 (○, *n* = 3) and 2002 (●, *n* = 4). Arrows show change between years. Bars denote standard error of each mean. The dotted line is the threshold at which the sum of RCIs for both crops is zero.

Table 2. Fresh weight of aboveground biomass collected throughout season. Calculated means of log transformed data are followed by back-transformed figures in parentheses. Means for a single crop followed by the same letter within a column are not significantly different, Tukey's test (*P* < 0.05).

Crop	Log plant biomass (back transformed to g $plant^{-1}$)		Log yield (back transformed to g m^{-2})	
Treatment	2001 (*n*=3)	2002 (*n*=4)	2001 (*n*=3)	2002 (*n*=4)
Basil				
BAS	5.72 (305) a	6.27 (528) a	8.36 (4264) a	8.91 (7391) a
S&B	1.22 (3) c	5.37 (215) b	2.94 (19) c	7.09 (1204) b
T&B	3.97 (53) b	5.96 (389) ab	5.54 (254) b	7.53 (1865) b
S.E. of diff.	0.18	0.28	0.18	0.28
Brussels sprout				
SPT	7.57 (1945) a	6.82 (915) b	9.34 (11350) a	8.57 (5282) a
S&B	8.17 (3545) a	7.75 (2319) a	9.25 (10363) a	8.82 (6795) a
T&S	7.67 (2137) a	7.24 (1389) ab	8.87 (7122) a	8.44 (4629) a
S.E. of diff.	0.19	0.17	0.19	0.17
Tomato				
TOM	8.20 (3626) ab	7.36 (1577) bc	9.68 (16058) a	8.85 (6981) a
T&B	8.60 (5410) a	7.92 (2752) a	9.51 (13535) a	8.84 (6884) a
T&S	7.82 (2477) b	7.26 (1419) c	8.37 (4307) b	7.81 (2468) b
S.E. of diff.	0.17	0.10	0.17	0.10

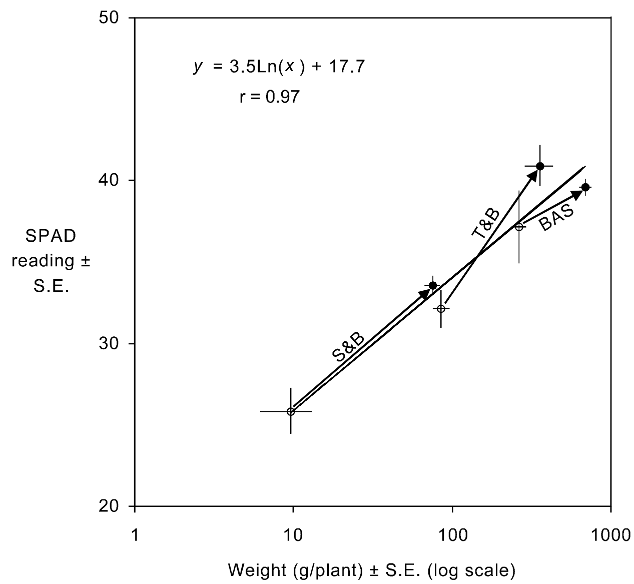

Figure 6. Relationship between relative chlorophyll content (SPAD reading) of basil leaves and fresh weight per basil plant at final harvest in 2001 (○, *n* = 3) and 2002 (●, *n* = 4). Basil was grown in pure stands (BAS), or in mixtures with tomato (T&B) or Brussels sprout (S&B). Arrows show change between years. Bars denote standard error of each mean. Trendline and equation show relationship between SPAD reading and plant weight for pooled data.

Tomato. More tomato biomass was removed in 2001 (12.3 kg m^{-2}) than in 2002 (5.7 kg m^{-2}). Fruit accounted for most (88% in 2001; 77% in 2002) of this biomass. The mean weight of individual tomatoes did not differ significantly between years (134 ± 4 and 121 ± 3 g $fruit^{-1}$ in 2001 and 2002, respectively), but each plant produced more fruits in 2001 (28.3 ± 3.0) than in 2002 (15.8 ± 1.4), reflecting a shorter harvest period, fewer harvests, and a lower yield per harvest in 2002.

Tomato plants grown with basil produced more fruits per plant (27.7 ± 3.4), than those grown in monoculture (20.6 ± 3.3) or with Brussels sprout companions (15.2 ± 2.1). Plants grown with basil companions produced more biomass than those grown in monoculture, or with Brussels sprout companions (Table 2). Tomato yields were reduced by Brussels sprout companions (Table 2). No relationship was observed between relative leaf chlorophyll content and tomato yield (data not shown).

Mixture LER. RY of primary and secondary crops in each mixture is shown in Figure 7. The sum of RYs for each mixture is the mixture LER, which tended to exceed one in 2002, but not in 2001 (Figure 7, Table 3). One crop in each mixture tended to dominate, accounting for more than two-thirds of LER. Tomato and Brussels sprout both dominated in mixtures with basil, and Brussels sprout tended to dominate in mixtures with tomato (Figure 7).

Brussels sprout accounted for 68 and 88% of the change in LER observed between years for the S&B and T&S combinations, respectively (Table 3). Basil accounted for 78% of the increase in the T&B combination.

The change in LER between 2001 and 2002 was due to Brussels sprout and tomato yields in pure stands falling more than in mixed plantings, and basil yields in mixtures increasing more than in pure stands.

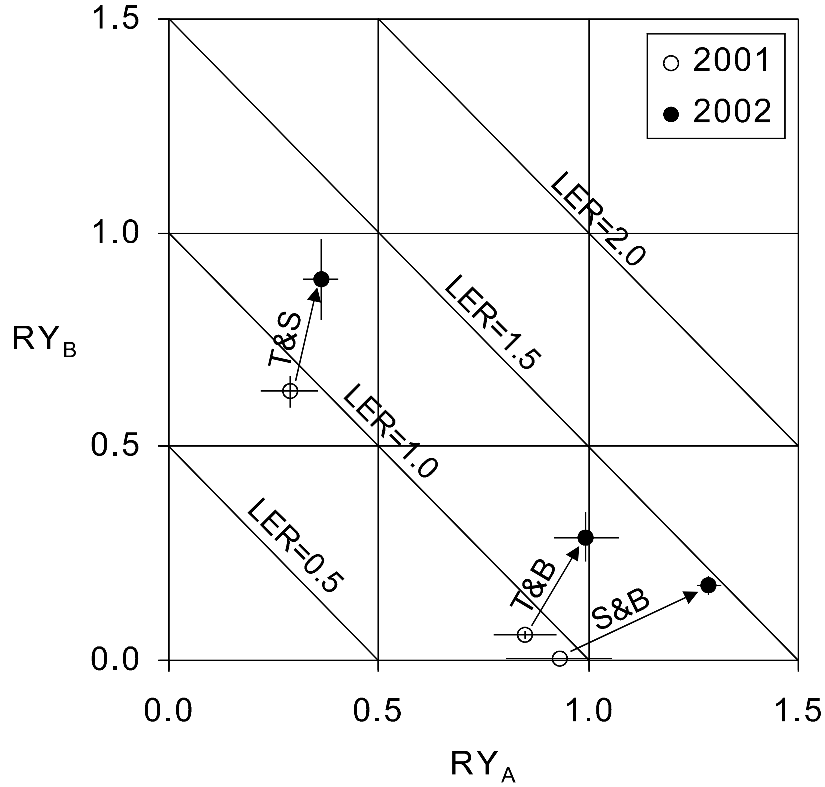

Figure 7. Relative yield of primary and secondary crops in mixtures (RY_A and RY_B, respectively) as a proportion of pure stand yields in 2001 (○, n = 3) and 2002 (●, n = 4). The sum of RYs for a mixture is the land equivalence ratio (LER). Arrows show change in LER for each treatment between years. Bars denote standard errors of each mean.

Table 3. Land Equivalence Ratio (LER) of three mixtures by year ($\bar{x}$ ± S.E.).

	LER	
Mixture	**2001 (*n*=3)**	**2002 (*n*=4)**
S&B	0.93 ± 0.13	1.46 ± 0.03*
T&B	0.91 ± 0.07	1.28 ± 0.05*
T&S	0.92 ± 0.10	1.25 ± 0.13

*Significantly different from one at the 0.05 probability level (one-tailed t-test)

DISCUSSION

This study evaluated the effect of mixed planting in the context of BIA garden systems grown according to the methods of Jeavons (2006). Most studies that calculate LER values use either an additive design, in which the density of the primary crop is held constant between mixed plantings and pure stands, or a replacement design, in which total plant density is held constant (Freckleton and Watkinson 2000, Jolliffe 2000). The former confounds polyculture and total plant density effects; the latter confounds polyculture and individual crop density effects. Following current BIA recommendations for plant spacing in mixed stands confounds all of these effects, and requires more land for mixed plantings than pure stands, as discussed below.

Jeavons (2006) recommends that inter-plant spacing in mixtures, s_{mix}, be set to the mean of the recommended spacing for the component crops, s_A and s_B, grown in pure stands:

$$s_{mix} = \frac{s_A + s_B}{2} \quad \text{Eq. 2}$$

The relationship between plant density, D, and inter-plant spacing, s, in a hexagonal lattice formed by offset rows in which inter-plant spacing is held constant within and between rows (e.g. Figure 1) is:

$$D = \frac{2}{\sqrt{3}s^2} \quad \text{Eq. 3}$$

Combining equations 1 and 2 gives the planting density in mixtures, D_{mix}, spaced according to Jeavons' recommendation:

$$D_{mix} = \frac{2}{\sqrt{3}\left(\frac{s_A + s_B}{2}\right)^2} \quad \text{Eq. 4}$$

Since Eq. 1 weights each crop equally, it appears to be based on an assumption of equal component crop proportions, yet Jeavons' planting diagrams (e.g. Figure 1) call for uneven mixture proportions. Planting density in Jeavons' mixtures is determined by the mean spacing of component crops, even though density is the inverse square of spacing. As a result, mixtures spaced according to Jeavons' recommendations require more land per plant than pure stands: The mixtures grown in this study required 20% more land, on average, than would two pure stands with the same total number of plants (Table 4).

Land use efficiency is often positively correlated with planting density (Jolliffe and Wanjau 1999, Park et al. 2002). High density planting is one of the reasons given by Jeavons for higher yields in biointensive systems (Jeavons 2006). Although this study found an advantage to mixed plantings in 2002, it likely underestimated the mixture advantage that would be achieved if the same land area were dedicated to the mixtures as to pure stands of the component crops. Calculation of the LER index uses pure stand yield in the denominator. A higher density in pure stands than mixtures is likely to result in higher pure stand yields and a lower LER value than would otherwise be expected.

Table 4. Plant density in mixed stands spaced according to popular BIA recommendations (Jeavons, Eq. 4) and recommendations introduced here (Bomford, Eq. 5). Mixed stand densities are derived from recommended densities for pure stands of component crops, assuming a primary:secondary crop ratio of 1:2. Additional land needed for mixtures spaced according to the popular BIA recommendation, relative to land needed for separate pure stands, is shown for the mixtures tested in this study. The new recommendations require the same amount of land for mixed plantings as for separate pure stands, assuming that pure stands and mixtures each contain the same total number of plants from each crop.

	Pure stand density (plants m^{-2})		Mixed stand density (plants m^{-2})		Additional land needed for BIA mixture (%)
Mixture	Primary crop	Secondary crop	Jeavons (Eq. 4)	Bomford (Eq. 5)	
S&B	5.7	12.8	8.2	10.5	21.5
T&B	4.3	12.8	6.9	10.0	31.2
T&S	5.7	4.3	4.9	5.2	6.0

A fairer comparison of mixture and pure stand yields would have mixture planting density, D_{mix}, set to the sum of densities of the primary and secondary crops in monoculture, D_A and D_B, respectively, each multiplied by their proportion in the mixture, p and 1-p, respectively:

$$D_{mix} = \frac{1}{\frac{p}{D_A} + \frac{1-p}{D_B}} \qquad \text{Eq. 5}$$

Inter-plant spacing can then be calculated from target density. In a hexagonal lattice the relationship between mixture spacing and component crop spacing in pure stands would be:

$$s_{mix} = \sqrt{\frac{2}{\sqrt{3}D_{mix}}} = \sqrt{\frac{2}{\sqrt{3}}\left(\frac{p}{D_A} + \frac{1-p}{D_B}\right)} = \sqrt{\left(ps_A^2 + (1-p)s_B^2\right)} \qquad \text{Eq. 6}$$

Equations 5 and 6 give similar results to Equations 4 and 2 if the component crops in a mixture have similar spacing (e.g. tomato and Brussels sprout), but increasingly divergent results as the recommended spacings of component crops diverge. When recommended spacings for component crops differ substantially (e.g. tomato and basil) Equations 5 and 6, introduced here, tend to recommend higher densities and tighter plant spacing than Equations 4 and 2, derived from Jeavons (2006). Recognizing that Equation 6 is more complex than Equation 2, I have made a spreadsheet available for download that calculates plant spacing and target density for mixed plantings in BIA systems (Bomford 2007, Figure 8). To my knowledge, this is the first such tool designed to calculate mixture densities based on both crop proportion and recommended density in pure stands. It is intended to provide spacing recommendations for field use, and to generate experimental designs allowing the calculation of relative land output values, which require that mixtures have the same number of plants, and occupy the same total land area, as pure stands of the component crops (Jolliffe 1997). Its use will avoid confounding total plant density with polyculture effects in comparisons of mixtures and pure stands without requiring constant plant spacing between mixtures and pure stands, as in substitution designs.

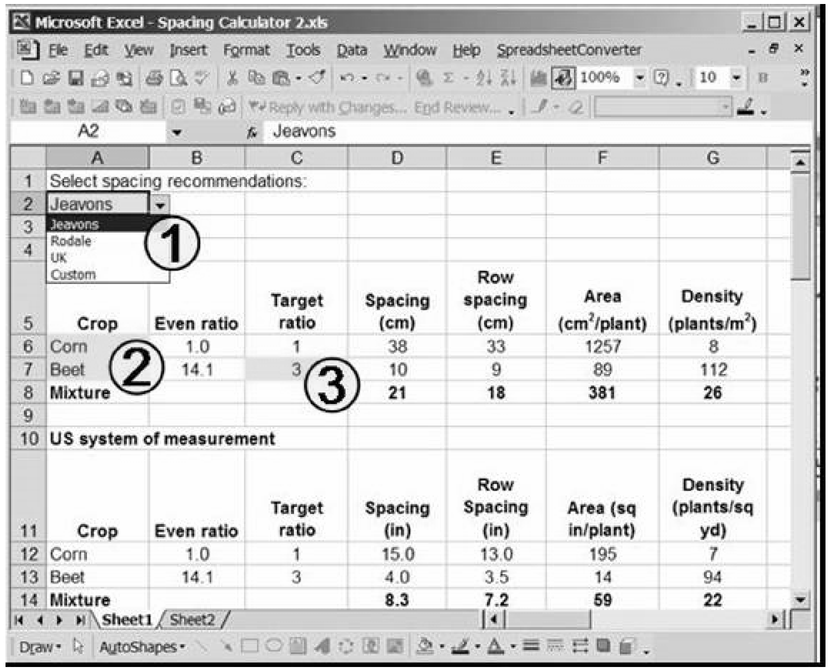

Figure 8. Screenshot of a spacing calculator available for download (Bomford 2007). Drop-down menus offer a selection of spacing recommendations for pure stands (①), primary and secondary crops (②), and crop ratios (③). Spacing recommendations and final planting densities are calculated for pure stands and mixtures in metric and US measurement units.

Mixed plantings made more efficient use of land than pure stands in 2002, but not in 2001. Tomato and Brussels sprout plants were transplanted into plots later in 2002 than in 2001 (Figure 2), and 2002 was drier than 2001 (Figure 3). Both of these differences likely contributed to smaller and less competitive tomato and Brussels sprout plants in 2002. Basil seems to have benefited from the reduced size of its companions: With more access to light it accumulated more chlorophyll and produced more aboveground biomass. Tomato and Brussels sprout also used land more efficiently when mixed together in 2002, but not in 2001, suggesting complementary use of resources when plants were smaller and moisture was more limiting. The observation supports the contention of Rao and Willey (1980) and Natarajan and Willey (1986) that mixtures offer a greater yield advantage over pure stands when moisture is limited, but does not agree with a recent model suggesting no effect of moisture availability on LER (Tsubo et al. 2005) or with an earlier report of a mixture yield advantage in a wet year but not in a dry one (Fisher 1976).

This study showed a relationship between SPAD readings and basil yield, but no relationship between SPAD readings and tomato or Brussels sprout yield. SPAD readings have previously been correlated with leaf chlorophyll content in a variety of crops including rice (Jiang and Vergara 1986), corn (Dwyer et al. 1991), wheat, barley, and triticale (Giunta et al. 2002). SPAD readings have also been correlated with yields of crops including corn (Blackmer and Schepers 1994), potato (Gianquinto et al. 2003) and cabbage (Westerveld et al. 2003). This effect is not consistent, however: Westerveld et al. (2003) report correlations between SPAD readings and cabbage in one year, but not another; and Martini et al. (2004) report higher SPAD readings in conventional tomato plants than organic, but higher yields from the organic tomatoes. The results suggest that tomato and Brussels sprout plants were not limited by nitrogen or light, but basil plants were.

Despite vigorous growth and superior competitiveness of Brussels sprout plants, most sprouts were bitter and elongated, rendering them unmarketable. These problems are associated with excessive heat or nitrogen (Rahn et al. 1993), and were more pronounced in 2002 than 2001. Brussels sprout is a cool season crop, while basil and tomato are warm season crops; their differing heat requirements make them poor companions for concurrent production. A previous attempt to transplant Brussels sprout into tomato or basil beds in mid-summer, for winter harvest, did not result in a marketable harvest because Brussels sprout plants did not compete successfully with companion crops that had a much earlier start (Bomford 2004).

Differences between 2001 and 2002 should not obscure the similarities that emerged between treatments across years. All crops showed a decrease in RCI and an increase in RY from 2001 to 2002, but the relationship between crops changed very little when evaluated by either of these indices (Figures 5 and 6): The stronger competitor in each mixture was the same in both years, and the proportion of LER accounted for by each crop was very similar. The crops mixed in this study had similar effects on one another in both years, supporting the idea that specific companion mixtures could be recommended with an expectation that they would offer consistent benefits to producers.

Both of the popularly recommended mixtures tested in this study included basil as a secondary crop. Basil was the least competitive crop of those tested, and it did not significantly reduce weight or yield of tomato or Brussels sprout grown with it, relative to pure stands. In 2002 individual tomato and Brussels sprout plants produced more aboveground biomass when grown in mixtures with basil than in pure stands. Tomato and Brussels sprout yields did not differ significantly between basil mixtures and pure stands, even though their density in basil mixtures was half their density in pure stands. This could be taken as evidence that basil enhanced growth of its companions, as claimed in some popular publications (e.g. Riotte 1975), or as evidence that the pure stand density of tomato and Brussels sprout was excessive, with the observed benefit due to the reduction in same-species neighbors, not the introduction of basil companions.

The biomass produced by individual tomato or Brussels sprout plants in tomato-Brussels sprout mixtures did not differ significantly from pure stands. Although the LER of this mixture was not significantly greater than one in either year, differences lacked significance due to variability between replicates: The T&S mixture showed the same tendency to increase between 2001 and 2002 as the other mixtures (Figure 7). Both tomato and brassica crops have been shown to inhibit growth of some other plant species through allelopathy (Kluson 1995, Kim 2001), but this study showed no evidence of antagonism between the two crops when mixed. The LER values of 0.92 and 1.25 calculated for Brussels sprout-tomato mixtures grown in 2001 and 2002 in this study are lower than the values of 1.70 and 1.63 calculated from data presented by Brown et al. (1985) for cabbage-tomato mixtures grown in 1981 and 1982 in Illinois. Neither study supports the assertion of popular manuals (Riotte 1975, Jeavons 2006) that tomato and brassicas should not be grown together due to mutual antagonism. The fact that Brussels sprout thrives in cooler conditions than tomato or basil is a better reason for choosing not to mix these crops.

SUMMARY AND CONCLUSIONS

1. Mixed plantings used land more efficiently than pure stands in BIA systems grown according to popular recommendations in 2002. No mixture advantage was observed in 2001. Water was a more limiting resource, and RCI was lower, for all crops in 2002. Results suggest that mixed planting can increase land-use efficiency of BIA systems under resource-limiting conditions.

2. Popular recommendations for calculating inter-plant spacing in mixed BIA beds tend to result in lower density in mixed plantings than in segregated pure stands with the same total number of plants. This difference is more pronounced as recommended spacings for component crops diverge. Current popular recommendations do not account for the proportion of each crop in a mixed planting. New recommendations are proposed to address these problems. A spreadsheet is available for download that calculates inter-plant spacing in mixed plantings according to the revised recommendations (Bomford 2007). The new recommendations are expected to improve land-use efficiency of mixed stands and allow a fairer comparison of mixed plantings and pure stands in BIA systems.

3. All mixtures consisted of one crop that faced more competition in the mixture than in pure stands (RCI > 0), and another that faced less (RCI < 0). Basil was the least competitive component crop, accounting for less than one-third of LER in mixed plantings, and the only crop for which relative leaf chlorophyll content was correlated with biomass production. Brussels sprout was the most competitive crop, accounting for at least two-thirds of LER.

4. Two mixtures popularly recommended for BIA systems (tomato and basil; Brussels sprout and basil) did not offer superior land-use efficiency to a popularly discouraged combination (tomato and Brussels sprout). The consistently poor marketable Brussels sprout yield in all treatments was probably due to excessive heat for the cool-season crop; it was not due to poor plant growth. Cool-season crops should not be mixed with warm-season crops for synchronous growth in mixed plantings.

REFERENCES

Andersen, J., C. Henriksen, J. Laursen, & A. Nielsen. 1999. Computerised image analysis of biocrystallograms originating from agricultural products. Computers and Electronics in Agriculture 22: 51-69.

Andow, D.A. 1991. Vegetational diversity and arthropod population response. Annual Review of Entomology 36: 561-86.

Barret, C.B. 1993. On price risk and the inverse farm size–productivity relationship. University of Wisconsin–Madison, Department of Agricultural Economics Staff Paper Series no. 369.

Beeby, J., J.W. Doran, & J. Jeavons. 2006. Biologically intensive agriculture - renewing earth and its people. In Proceedings 18th World Congress of Soil Science.

Blackmer, T.M., and J.S. Schepers. 1994. Techniques for monitoring crop nitrogen status in corn. Communications in Soil Science and Plant Analysis 25:1791–1800.

Bomford, M.K. 2007. Companion plant spacing calculator. Kentucky State University Organic Agriculture Working Group website. http://organic.kysu.edu/Companion_spacing.html.

Bomford, M.K. 2004. Yield, pest density, and tomato flavor effects of companion planting in garden-scale studies incorporating tomato, basil, and Brussels sprout. PhD thesis, West Virginia University.

Bradley, F.M. & B.W. Ellis 1992. All-New Encyclopedia of Organic Gardening. Rodale Press, Emmaus, PA.

Brown, J.E., W.E. Splittstoesser, and J.M. Gerber. 1985. Production and economic returns of vegetable intercropping systems. Journal of the American Society for Horticultural Science 110: 350-353.

Bouyouris, K., K. Cassman, & S. Babagiouris. 2006, Biointensive agriculture in Crete, Greece: A companion for the poor and the rich. In Proceedings 18th World Congress of Soil Science.

Doran, J.W., C. Palm, F. Kirschenmann, & K. Cassman. 2006. Biologically intensive agriculture: Moving towards a sustainable future for all. In Proceedings 18th World Congress of Soil Science.

Drinkwater, L.E. 2002. Cropping systems research: Reconsidering agricultural experimental approaches, HortTechnology 12: 355-361.

Dwyer, L.M., M. Tollenaar, and L. Houwing. 1991. A nondestructive method to monitor leaf greenness in corn. Canadian Journal of Plant Science 71:505–509.

Finch, S., H. Billiald, & R.H. Collier. 2003. Companion planting - do aromatic plants disrupt host-plant finding by the cabbage root fly and the onion fly more effectively than non-aromatic plants? Entomologia Experimentalis et Applicata 109: 183-195.

Fisher, N.M. 1976. Studies in mixed cropping I: Seasonal differences in relative productivity of crop mixtures and pure stands in the Kenya highlands. Experimental Agriculture 13: 177-184.

Freckleton, R.P., and A.R. Watkinson. 2000. Designs for greenhouse studies of interactions between plants: an analytical perspective. Journal of Ecology 88: 386-391.

Gao, G. and Bergefurd, B. 1999. Growing, Harvesting, and Using Culinary Herbs in the Home Garden. Ohio State University Extension Factsheet HYG-1612-99. http://ohioline.osu.edu/hyg-fact/1000/1612.html.

Gianquinto, G., P. Sambo and S. Bona. 2003. The use of SPAD-502 chlorophyll meter for dynamically optimizing the nitrogen supply in potato crop: A methodological approach. Acta Horticulturae 627:217-224

Giunta, F., R Motzo, and M. Deidda. 2002. SPAD readings and associated leaf traits in durum wheat, barley and triticale cultivars. Euphytica 125: 197-205.

Grace, J.B. 1995. On the measurement of plant competition intensity. Ecology 76: 305-308.

Hart, Robert D. 1986. Ecological framework for multiple cropping systems. In Multiple Cropping Systems, Charles A Francis (ed.). 40-56. New York: Macmillan.

Held, D.W., P. Gonsiska, and D.A. Potter. 2003. Evaluating companion planting and non-host masking odors for protecting roses from the Japanese Beetle (Coleoptera: Scarabaeidae). Environmental Entomology 96: 81-87.

Holt, B.F., and I.K. Smith. 1998. Small-scale intensive cultivation methods: the effects of deep hand tillage on the productivity of bush beans and red beets. American Journal of Alternative Agriculture 13: 29-39.

Jeavons, J.C. 2001. Biointensive Sustainable Mini-Farming I: The Challenge. Journal of Sustainable Agriculture 19: 49-63.

Jeavons, John. 2006. How to grow more vegetables than you ever thought possible on less land than you can imagine. 7th edition, first published 1974. Ten Speed Press, Berkeley, CA.

Jiang, X.X., and B.S. Vergara. 1986. Chlorophyll meter (SPAD-501) to quantify relative cold tolerance in rice. International Rice Research Newsletter 11:10–11.

Jolliffe, P.A. 1997. Are mixed populations of plant species more productive than pure stands? Oikos 80: 595-602.

Jolliffe, P.A. 2000. The replacement series. Journal of Ecology 88: 371-385.

Joliffe, P.A., and F.M. Wanjau. 1999. Competition and productivity in crop mixtures: Some properties of productive intercrops. Journal of Agricultural Science 132: 425-435.

Kanton, R.A.L. and M.D. Dennett. 2004. Water uptake and use by morphologically contrasting maize/pea cultivars in sole and intercrops in temperate conditions. Experimental Agriculture 40: 201-214.

Kim, Y.S. 2001. Allelopathic effects of some volatile substances from the tomato plant. Journal of Crop Protection 4: 313-321.

Kluson, R.A. 1995. Intercropping allelopathic crops with nitrogen-fixing legume crops. In Allelopathy: Organisms, Processes, and Applications. Chapter 5 in K.M.M. Dakshini and F.A. Einhellig (eds.). Wiley Publishing, Hoboken NJ. 389 pp.

Martini, E.A., J.S. Buyer, D.C. Bryant, T.K. Hartz, and R.F. Denison. 2004. Yield increases during the organic transition: Improving soil quality, or increasing experience? Field Crops Research 86: 255-266.

Miles, C., Granatstein, D., and Stone A. (eds.). 2002. Proceedings Northwest Symposium on Organic and Biologically Intensive Farming. Nov. 8, 2002, Yakima, WA. 48 pp.

Medvecky, B.A. 2006.The need to formally assess biointensive agriculture practices and their impact on Kenyan smallholder agriculture, in Proceedings 18th World Congress of Soil Science.

Mbugwa, G.W., E.C. Fernandes, M.J. Pfeffer, E. & Rodriguez. 2006. The impact of biointensive cropping on yields and nutrient contents of collard greens in Kenya. In Proceedings 18th World Congress of Soil Science.

Natarajan, M., and R.W. Willey 1986. The effects of water stress on yield advantages of intercropping systems. Field Crops Research 13: 117-131.

Omondi, E.C., G.W. Mbugwa, J. Jeavons, B. Murambakania, R. Nyambori, M. Wamalwa, E. Mulegwa, S. Mardigian, & J. Okomba1. 2006. Potential of biologically intensive agriculture for feeding people in Kenya: A case study of Manor House Agricultural Centre activities. In Proceedings 18th World Congress of Soil Science.

Oyejola, B.A. and R. Mead. 1982. Statistical assessment of different ways of calculating Land Equivalent Ratios. Experimental Agriculture 18: 125-138.

Park, S.E., L.R. Benjamin, and A.R. Watkinson. 2002. Comparing biological productivity in cropping systems: a competition approach. Journal of Applied Ecology 39: 416-426.

Pia, J.F. 2006. CIESA project, a biointensive model for food security in Argentina. In Proceedings 18th World Congress of Soil Science.

Pfeiffer, E., 1931. Studium von Formkräften an Kristallizationen. Naturwissenschaftliche Sektion am Goetheanum, Dornach.

Rahn, C.R., C.D. Paterson, and L.V.V. Vaidyanathan. 1993. Improving the use of nitrogen in Brassicae rotations. Acta Horticulturae 339: 207-218.

Rao, M.R. and R.W. Willey. 1980. Evaluation of yield stability in intercropping: Studies on sorghum/pigeonpea. Experimental Agriculture 16: 105-116.

Riotte, Louise 1975. Carrots Love Tomatoes: Secrets of Companion Planting for Successful Gardening. Storey Books, Pownel, VT.

SAS Institute. 2001. JMP, version 4. Cary, NC.

Smith, H.A. and R. McSorley, 2000. Intercropping and pest management: A review of major concepts. American Entomologist 46: 154-161.

Theunissen, J. 1997. Intercropping in field vegetables as an approach to sustainable horticulture. Outlook on Agriculture 26: 95-99.

Tsubo, M., S. Walker, and H.O. Ogindo. 2005. A simulation model of cereal–legume intercropping systems for semi-arid regions II. Model application. Field Crops Research 93: 23-33.

Vandermeer, J. 1989. The Ecology of Intercropping. Cambridge University Press, Cambridge.

Watanabe, S., Y. Hatanaka, and K. Inada. 1980. Development of a digital chlorophyll meter: I. Structure and performance. Japanese Journal of Crop Science 49: 89-90.

Westerveld, S.M., A.W. McKeown, M.R. McDonald, and C.D. Scott-Dupree. 2003. Chlorophyll and nitrate meters as nitrogen monitoring tools for selected vegetables in southern Ontario. Acta Horticulturae 627: 259-266.

de Wit, C.T. 1960. On competition. Verslagen Landbouwkundige Onderzoekigen 66: 1-82.

Willey, R.W. 1979. Intercropping – its importance and research needs. Part 1. Competition and yield advantages. Field Crops Abstracts 32: 1-10.

Willey, R.W. and D.S.O. Osiru. 1972. Studies on mixtures of maize and beans (*Phaseolus vulgaris*) with special reference to plant population. Journal of Agricultural Science 79: 519-529.