Impact of Cutting Pressure on Yield, Quality, Root Carbohydrates, and Survival of Spring-harvested or Summer-forced Asparagus

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Abstract. Excessive cutting pressure (CP) early in the lifespan of an asparagus (*Asparagus officinalis* L.) plantation may weaken and reduce yields and quality. The objective of this research was to determine how increasing CP affects yield, quality, and survival of spring-harvested and summer-forced asparagus. ‘Jersey Gem’ asparagus was harvested for 4 years (1999–2002) in spring or summer-forced on 1 Aug. using the following CP (weeks/year from 1st to 4th years, respectively): 2, 3, 4, 6 (low), 3, 4, 5, 7 (medium), and 4, 5, 8, 10 (high). In all harvest years, as CP increased, marketable number and weight increased. Yield in spring harvest seasons significantly increased with each increase in CP. In summer, yield significantly increased only when high CP was used with equivalent yields at low and medium CP. With summer forcing, there were 48% and 55% fewer large spears at medium and high CP, respectively, compared to the same CP used during spring harvest seasons. Stands tended to decrease with CP from 1997 to 2003, but these differences were not significant and not severe enough to kill the plants. Yearly root fructose concentrations (RFC) with all CP increased yearly from 1999 to 2001 and plateaued from 2002 to 2003. From 1999 to 2002, RFC increased 53%, 27%, 13%, and 13% in unharvested control, low, medium, and high CP, respectively, indicating that with a greater CP, RFC decreased. RFC in summer-forced asparagus was significantly less than spring-harvested in 83% of all sample months. RFC in spring-harvested asparagus was similar to unharvested asparagus in February, March, April, November, and December; however, in all other sample months, spring-harvested RFC was significantly lower than unharvested control plants. The highest CP scheme is appropriate for spring-harvested asparagus based on greatest marketable yields and acceptable cull losses. For summer-forced asparagus, the lowest CP scheme is more appropriate based on acceptable marketable yields and to avoid undue plant stress verified by unacceptably large cull losses mostly attributed to spindly spear size and lower RFC.

Domestic production of asparagus (*Asparagus officinalis* L.) in the United States usually occurs from January to July with imports increasing from late summer through fall and early winter. Forcing asparagus into production in late summer and fall may provide a lucrative alternative enterprise for growers. Yield depends on the availability of accumulated carbohydrates in the storage roots elaborated by fern activity in the previous season before spear harvest, and possibly also in preceding years (Paschold et al., 2002). Previous research in coastal South Carolina indicated that within a 5-year period after transplanting, spring-harvested asparagus yields declined because of plant death. Summer-forced asparagus yielded better and lived longer than normal spring production (Dufault, 1994, 1995, 1999). Productive lifespan of spring-harvested asparagus, however, was only 2 (Dufault, 1994) to 3 years (Dufault, 1995; Dufault, 1999). Short lifespan was caused by inferior variety choice and fern vigor after the harvest season. Asparagus fern growing season after spring harvest in coastal South Carolina lasts >7 months. Dufault (1995, 1999) suggested that the capacity for aged fern to produce carbohydrates

was severely reduced and stored root carbohydrates were used for growth and development processes after midsummer. Three-month-old asparagus fern reached greatest photosynthetic efficiency in tropical locations like Taiwan, but net CO₂ assimilation rate declined after 3 months to a minimum about 5 months old (Lin and Hung, 1978). Yearly repetitions of long duration harvests and allowing aged fern to remain on the plants, may deplete stored carbohydrates in late summer and fall, reduce plant vigor, stand, yield and ultimately longevity (Dufault, 1994; 1995; 1999). Mother stalk asparagus culture developed in Taiwan has been used there commercially since 1961 to increase quality and yields in tropical and subtropical climates (Wang, 1965). Dufault (1999) found that a modified mother stalk culture system was unsuccessful because too much time was required to establish mother stalks and mother stalks caused apical dominance, which prevented major spear emergence and high yields.

The yield superiority of the summer forcing systems has been related to 1) maximum carbohydrate production during peak photosynthetic efficiency in spring, 2) removal of aging fern by midsummer, 3) postharvest development of new efficient fern producing ample carbohydrates for spring spear emergence, and 4) maintenance of

the best seasonal balance between accumulation and depletion of root carbohydrates (Dufault, 1999). Removal of aged fern in midsummer with summer forcing rejuvenated the summer-forced plants and reduced stand loss by 38% over a 6-year period (Dufault, 1999).

Coastal South Carolina experiences tropical summers and subtemperate winters. Based on previous studies (Dufault, 1994, 1995, 1999), stand loss was too great and longevity of asparagus plantations much too short in spring-harvested asparagus. Harvest duration is important in asparagus production to reap the greatest yields, but excessive extension of the harvest season may deplete root carbohydrates, reduce recovery ability, plant vigor and longevity. Williams and Garthwaite (1973) found that increasing the harvest season from 2 to 4 weeks, increased yields in the first 2 years of production, but reduced yields in the third to fifth years. Shelton and Lacy (1980) found that harvesting for 4 to 6 weeks in the second year after transplanting crowns and 8 to 10 weeks the following year, reduced yields significantly in the fourth year after transplanting and decreased spear diameter and root carbohydrates. It is thought that asparagus in the southeastern U.S. may require very mild cutting pressure (CP) initially to prevent excessive stress that ultimately kills the plants by the fourth harvest year. Paschold et al. (2002) suggested that CP should be reduced progressively from 8 to 6 weeks as the asparagus plants age since older plants need more time for fern development and carbohydrate accumulation. The objective of this research was to determine how CP affects yield, root fructose content (RFC), quality, survival of spring-harvested and summer-forced asparagus.

Materials and Methods

On 16 Oct. 1996, 10-week-old ‘Jersey Gem’ asparagus seedlings were transplanted in the bottom of 10 cm deep furrows 0.6m apart in single rows spaced 1.8 m apart from bed center in a field at the Clemson Coastal Research Center, Charleston, S.C. The soil was a Yauhannah loamy fine sand (Aquic Hapludults). Each plot consisted of a single bed containing 44 transplants (35,864 plants/ha). In Spring 1997, the soil was ridged about 20 cm above normal ground level before spear emergence and maintained at that height for 5 years using no-till. Standard commercial fertilization and cultural practices were used during the course of the experiment (Cook, 1992). Fern vigor was encouraged without harvest until Spring 1999 when first harvest began. ‘Jersey Gem’ asparagus was harvested for four years (1999–2002) in spring or summer-forced Aug. 1 using the following CP (weeks/year from first to fourth years, respectively): 2, 3, 4, 6 (low), 3, 4, 5, 7 (medium), and 4, 5, 8, 10 (high). The harvest system treatments are outlined in Table 1. Four replications of each harvest system were arranged in a randomized complete block design with a factorial combination of harvest years (1999 to 2002), harvest seasons (spring or summer) and harvest CP (three levels considered low, medium, and high with CP

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increasing in duration yearly). Stand counts were taken yearly each spring, 1 month after spear emergence from 1996 to 2003. Since the plants were spaced 0.6 m apart, once stands were established and recorded, counting blank areas down the planted row could be deducted from the original surviving plants. In August 2003, plant populations were recorded and stand loss over the 7-year period calculated.

From March 1999 to June 2003, root samples from each plot were cored using a soil probe within the first week of every month and carbohydrate levels were determined as described by Dufault (1994). About 10 samples in a 27-m row length were taken in each replication which initially contained 44 plants. The root cores contained about 20 g fresh root material that was all ground and blended together and to yield about 1 g dry weight for analysis. In total, 52 monthly root samples for carbohydrate analysis were taken over the experimental period. In addition, to clarify the treatment effects on RFC, the monthly samples were grouped into four growth stages of asparagus, tailored to the specific developmental period that asparagus plants experience in this geographical region. The first growth stage was termed preemergence/late dormancy and included January through March samples. During the early phase of this growth stage (Jan.), asparagus ferns were totally senescent, brown, and desiccated and the crowns were in full dormancy. Dead fern was removed in January and spears had not emerged. In early February, the soil began to warm and the crowns begin to come out of dormancy with significant spear emergence usually occurring in mid-March. The carbohydrate status at this stage was important physiologically because yield depends totally on stored carbohydrates to fuel spring fern development. The second growth phase, termed spear production/fern development, occurred from April to July. During this stage, the greatest demand on stored carbohydrates occurred with carbohydrate concentration usually declining steeply in Apr. and gradually stabilizing in June in response to the fern development. In the third growth stage termed fern rotation/summer rejuvenation, the fern was approaching late maturity, turned pale green with some yellowing. At this point, all fern was mowed to the ground in spring-harvested and summer-forced plants and summer-forced harvests began; spring-harvested plants produced new efficient fern for carbohydrate storage until fall senescence in Nov. The last growth stage was autumnal senescence from November to December when all fern gradually yellowed, withered and died by the end of the year. Spring-harvested asparagus usually recovered to an adequate carbohydrate level by this stage; however, summer-forced plants did not recover until the following June. There were four replications of carbohydrate data in a factorial combination of harvest year, harvest seasons (spring or summer), growth stages (four periods) and CP (low, medium, and high).

Spears were harvested at the soil surface with a knife, and trimmed to a 23-cm length and graded into either marketable or cull quality categories based on U.S. Department of Agriculture (USDA) standards (USDA, 1977).

The diameter of each marketable spear butt was measured and graded as large (>1.3 cm), medium (0.8 to 1.3 cm). Spears smaller than medium were considered cull.

All data were subjected to ANOVA using the GLM procedure of SAS (SAS Institute Inc., Cary, N.C.). If the F test was significant at $P = 0.05$, the means were separated by LSD at $P = 0.05$. The relative importance of harvest factors was determined by partitioning the total sum of squares for treatments into main and interaction effects and expressing these individual contributions to variation as a percentage of the sum of squares for the model (composed of only those sources of variation in the ANOVA). The value of these percentages is that they become very useful indicators of which factors were more important in affecting growth, quality and yield variables relative to the other factors.

Results and discussion

Marketable yield. Harvest year had the greatest effect on asparagus yield over the course of the experiment. Harvest year had a dynamic effect on yield, however, interacting with harvest season and CP. These significant interactions (year $\times$ season, year $\times$ CP, and season $\times$ CP) were constantly changing due to 1) the continuing maturation of the asparagus planting and 2) the influence of forcing superimposed over time on a maturing asparagus planting. More than 50% of the variation in total marketable weight and numbers was assigned to the main effect of harvest years (Table 2). The assignment of importance, however, was not based solely on main effects, but on the interactions. The year $\times$ CP $\times$ harvest season interaction was not significant, therefore, two-way interactions were used to determine the influence of the factors in a stepwise fashion.

As the harvest years progressed, the influence of harvest seasons became distinct with every year showing different outcomes. Main effects and interactions between harvest season and year accounted for about 75% and 68% of the variation in marketable number and weight, respectively (Table 2). In the first harvest year, there was no difference in marketable weight and number between spring harvesting and summer forcing (pooled over CP) (Table 3). In 2000 and 2001, however, summer forcing became superior to spring harvesting with 44% and 34% greater weight in summer-harvested yields than spring yields due to 48% and 49% more spears produced in 2000 and 2001, respectively. By 2002, summer forcing apparently became stressful since marketable weight was 25% lower than spring, but the number of spears produced was actually 10% higher with summer forcing. Lighter, thinner spears were

the major difference between summer- and spring-harvested asparagus. Individual spear weight and diameter progressively decreased with harvest year, declining 7%, 6%, 22%, and 32% from 1999 to 2002, respectively, especially with summer forcing. Williams and Garthwaite (1973) and Shelton and Lacy (1980) reported that increasing the length of the harvest season in second and third years, respectively, reduced yields in latter years.

In all harvest years, in general, the longer the harvest season progressed, marketable number and weight tended to increase, but because of the dynamic relationship between the effects of the harvest treatment and the maturity of the planting, each year the effect of CP varied (Table 4). In the first 2 years, weight and numbers were the same with medium and high CP even though marketable yield was numerically greater with high versus medium CP. In the third harvest year, however, total marketable number significantly increased incrementally with CP. In the last harvest year, total marketable number increased from low to medium CP, but leveled off at the medium CP without significant increases with high CP.

Spring-harvested asparagus did not react the same to CP as summer-forced asparagus (Table 5). Marketable yield in spring significantly increased with every increase in CP (pooled over years). In summer, yield significantly increased only when high CP was used with equivalent yields in low and medium CP. This outcome may be due to the fact that cooler ambient temperatures predominate during early spring harvesting. As spring harvest season progressed, ambient temperatures increased yet the prescribed number of harvest days had elapsed at the lower CP. Conversely, it required more harvests for the higher CP, which occurred during warmer ambient temperatures during late spring, which stimulated spear emergence and greater yield. During summer forcing, field temperatures are consistently greater which changes the rate of spear emergence.

Spear quality. Individual spear weight, length and diameter and head tightness are the most obvious determinants of quality with asparagus. The larger the spear diameter, the fewer needed to produce a marketable bunch. The production of larger diameter spears is a strong indicator of vigor in contrast to plants that produce a majority of smaller diameter spears. Plants grown under excessive CP stress may produce a majority of smaller spears. Similar to marketable weight and numbers, the effect of the experimental treatments on spear quality was also dynamic. Both the main effects of year and harvest season and their interaction accounted for 79% of variation in spear weight and the production of both large- and

Table 1. Number of spring and summer harvests at different cutting pressures over 4 years.

Harvest season	Cutting pressure	No. of harvests per year (cumulative)			
		1999	2000	2001	2002
Spring	Low	14	19 (33) ^a	28 (61)	42 (103)
	Medium	21	26 (47)	43 (90)	56 (146)
	High	28	33 (61)	56 (117)	70 (187)
Summer	Low	14	21 (35)	30 (65)	43 (108)
	Medium	21	28 (49)	44 (93)	57 (150)
	High	28	35 (63)	58 (121)	71 (192)

Table 2. Sources of variation² in the analysis of variance for the effects of harvest season and cutting pressure on asparagus yield from 1999 to 2002.

Year	Marketable yield (plot/year)		Cull yield (plot/year)		Spear butt diam (%)		Individual spear wt (g)
	No.	Wt (kg)	No.	Wt (kg)	Large	Medium	
Replication	<1	<1	1***	1**	<1	<1	2
Year (Y)	59***	56***	32***	28***	35***	35***	31***
Season (S)	8***	0	38***	44***	34***	34***	33***
Cutting pressure (CP)	12***	12***	13***	15***	3***	3***	3***
Y × S	8***	12***	7***	5***	12***	12***	13***
Y × C	2**	3**	4***	3***	0	0	2
S × C	<1	2**	2***	2***	2**	2**	0
Y × S × C	<1	2	<1	<1	<1	<1	<1
Error	8	12	2	<1	12	12	15

²The sum of squares for each factor in the ANOVA converted to a percentage of the total sum of squares.***, ***, Significant at $P = 0.05, 0.01, 0.001$, respectively.

Table 3. Interaction of harvest season and year on asparagus yield (pooled over cutting pressures).

Year	Harvest season	Marketable yield (plot/year)		Cull yield (plot/year)		Spear butt diam (%)		Individual spear wt (g)
		No.	Wt (kg)	No.	Wt (kg)	Large	Medium	
1999	Spring	280 d ^z	4.95 f	130 a	1.40 f	57 a	43 f	17.6 a
	Summer	254 d	4.10 f	431 d	4.90 c	36 c	64 d	16.3 b
2000	Spring	258 d	3.61 f	118e	0.79 g	26 d	74 c	14.0 c
	Summer	498 c	6.48 e	447 cd	2.77 e	26 d	74 c	13.1 cd
2001	Spring	490 c	8.03 d	142 e	0.85 g	45 b	55 e	16.4 b
	Summer	966 a	12.21 b	887 d	6.16 b	18 e	82 b	12.7 d
2002	Spring	872 b	14.28 a	495 c	3.99 d	35 c	65 d	16.4 b
	Summer	665 a	10.68 c	1313 a	7.42 a	11 f	89 a	11.1 e

^zMeans in columns are significantly different by LSD at $P = 0.05$.

Table 4. Interaction of year and cutting pressure on asparagus yield (pooled over harvest season).

Year	Cutting pressure	Marketable yield (plot/year)		Cull yield (plot/year)	
		No.	Wt (kg)	No.	Wt (kg)
1999	Low	156 g ^z	2.67 g	163 g	1.82 g
	Medium	268 fg	4.67 ef	283 f	3.24 e
	High	377 ef	6.23 de	394 e	4.39 c
2000	Low	284 f	4.04 fg	199 g	1.35 h
	Medium	376 ef	5.04 ef	282 f	1.69 gh
	High	476 de	6.07 de	381 e	2.30 f
2001	Low	494 d	7.02 d	317 f	2.42 f
	Medium	705 c	9.57 c	537 d	3.56 de
	High	984 ab	13.76 a	691 c	4.54 c
2002	Low	788 c	11.18 bc	570 d	3.72 d
	Medium	916 b	12.66 ab	862 b	5.37 b
	High	1051 a	13.61 a	1280 a	8.02 a

^zMeans in columns are significantly different by LSD at $P = 0.05$.

medium-sized spears (Table 2). In three out of four years, heavier spears with larger diameters were greater in spring than summer with the converse relationship true for medium diameter spears (Table 3). Dufault (1995) reported an opposite effect that more large diameter spears were produced in summer forcing than spring using the 'UC 157 F₁' variety, which was considered to be an inferior variety for spring production and better suited for summer forcing. Although marketable yields in three out of four years were higher from summer forcing, the majority of spears in summer production were medium diameter versus large spears in the spring harvests. If the market demands larger versus medium sized spears, summer-forced asparagus is then considered lower quality than spring harvested asparagus. Increasing the CP during spring harvesting did not affect the production of large spears, but increasing CP during summer forcing, increased the production of medium sized spears significantly with fewer large diameter spears (Table 5). There were 48% and 55% fewer large spears at medium and high CP, respectively, in summer forcing versus the

same CP applied during spring. In addition to RFC, soil and air temperatures affect spear size especially with summer-forced plants when the soil temperatures are usually over 32 °C during summer season. High temperatures speed the bud break, spear emergence and elongation rate greatly. Asparagus growth rates approximately doubles with each increase of 10 °C (Culpepper and Moon, 1939). Even if an asparagus plant's root system is fully charged with RFC, high temperatures may override RFC content in importance and smaller diameter spears may result because the plants are growing extremely fast. Commercially, twice daily harvests may be necessary for summer-forced asparagus since spears in the morning may be undersized, but by later in the afternoon, they may have stretched beyond maximum lengths and even feathered. During the cooler spring harvest season, field temperatures may be 20 degrees lower, the growth rate slowed and the plant more likely to produce a spear of larger girth.

Cull yield. Unlike marketable yield which was more affected by harvest year, about 39% and 45% of the variation in cull weight and

numbers, respectively, was assigned to the main effect of harvest season, with the main effect of harvest year accounting for lesser, but significant portions of variation (Table 2). Of the two factors, harvest season was a stronger effector of cull production than harvest year. Similar to marketable yield, however, cull production in relation to the experimental factors was dynamic as indicated by significant interactions between year × harvest season, year × CP, and harvest season × CP.

Cull production consistently was lower in spring versus summer harvest seasons. Sixty-nine percent, 78%, 84%, and 68% less culls were produced in spring than summer harvest seasons from 1999 through 2002, respectively (Table 3). Cull yield in weight were 71%, 71%, 84%, and 46% more in summer than spring harvest seasons and most cull losses were due to spindly sized spears not making the minimum diameter. In most cases, as CP increased in each year, cull number and weight increased (Table 4) and this effect was much stronger in summer seasons than in spring (Table 5).

Plant survival. The two major aftermaths of using high CP during the summer forcing season were increased cull yield and the production of thinner marketable spears, both indicators of inferior plant vigor and plant stress. Stand counts were taken yearly to determine if any imposed treatment accelerated plant demise. From 1997 to 2003, the total stand reduction in control plots that never were harvested (except summer fern removal) was 16%. Although there was a tendency for stand loss to increase with CP levels in spring (16% to 18%) as well as summer (11% to 16%, respectively), these differences were not significant. In fact, stands in unharvested control were similar to harvested stands even after high CP. It was concluded that even though cull yields increased and spear diameters decreased with increasing CP in spring

Table 5. Interaction of harvest season and cutting pressure on asparagus yield (pooled over harvest year).

Harvest season	Cutting pressure	Marketable yield (kg/plot/year)	Cull yield (plot/year)		Spear butt diam (%)	
			No.	Wt (kg)	Large	Medium
Spring	Low	5.09 c ^z	118 f	0.93 f	41.4 a	58.6 d
	Medium	8.22 b	216 e	1.71 e	41.8 a	58.0 e
	High	9.84 a	336 d	2.63 d	39.1 a	60.9 c
Summer	Low	7.36 b	506 c	3.73 c	29.0 b	71.0 b
	Medium	7.75 b	766 b	5.22 b	21.6 c	78.4 a
	High	9.99 a	1036 a	6.99 a	17.6 c	82.4 f

^zMeans in columns are significantly different by LSD at $P = 0.05$.

Table 6. Sources of variation in the analysis of variance for the effects of harvest year, season, sample month and harvest duration and their interactions on the total variation in root carbohydrates from 1999 to 2003.

Source of variation ^z	Fructose (mg·g ⁻¹ root dry wt)
Replication	<1
Month (M)	18***
Year (Y)	12***
M × Y	26***
Season (S)	1***
S × M	2***
S × Y	1**
S × M × Y	2***
Cutting pressure (CP)	1**
CP × M	<1
CP × Y	1*
CP × M × Y	2
CP × S	<1
CP × S × M	<1
CP × S × Y	<1
CP × S × M × Y	2
Error	30

^zThe sum of squares for each factor in the ANOVA converted to a percentage of total sum of squares.

***, **, *Significant at $P = 0.05$, 0.01, and 0.001, respectively.

and especially summer, this stress was not severe enough to kill the plants. Apparently, asparagus varieties differ in tolerance and response to summer forcing since in previous work, productive lifespan of spring-harvested asparagus was only 2 to 3 years with 'Jersey Giant' and 'UC 157 F₁' varieties, respectively (Dufault, 1995; 1999). 'Jersey Gem' asparagus variety tolerates summer forcing and is superior to 'Jersey Giant' and 'UC 157 F₁' in previous work.

Root fructose content. In temperate climates, the usual sequence of seasonal changes in root resources starts with a) a fully charged root (RFC) and maximum bud number at the end of the winter, b) deplete the storage and bud number by harvesting and post harvest fern development, and c) recharge of RFC and production of new buds and roots through fern photosynthesis with export of RFC to the root system during autumn before winter dormancy (Wilson et al., 1999). Fern removal and rejuvenation in our study add another stage to the sequence described by Wilson et al. (1999). Fern removal in late July is mandatory in the southeast to remove aging inefficient fern and rejuvenate plants that are spring-harvested and summer-forced. Removal of summer fern adds another dimension to the RFC dynamics proposed by Wilson et al. (1999) in New Zealand that does not practice summer forcing. CP stress and forcing over the 5 harvest years created increased plant stress affecting spear diameters and cull production, but not plant survival. Although not lethal, these

Fig. 1. Monthly root fructose of asparagus harvested in spring or summer forced (pooled over all cutting pressures) and averaged from March 1999 to June 2003. In coastal South Carolina, major asparagus spear emergence begins in mid-March. All ferns in spring-harvested and summer-forced plots were mowed down on 1 Aug. The F test of the growth stage main effect was significant at $P = 0.05$, mean separation by LSD at $P = 0.05$.

imposed stresses were expected to affect RFC in the storage roots. Most variation in RFC was attributed to the main effects of sample month and year, but especially to the interaction between these two factors, which totaled 56% of total variation (Table 6). Although the main effect of harvest season was significant and interacted with sample month and harvest year, only 6% of total variation was assigned collectively to those factors. Likewise, the main effect of CP and its interaction with harvest year only accounted for 2% of the variation in RFC which is considered negligible. The variation assigned to uncontrolled error was high, indicating other unknown, uncontrolled factors affected RFC; however, 70% of the variation was explained by experimental factors in the ANOVA.

RFC with spring-, summer-harvested, and unharvested, showed at least two peaks of fructose concentration in February and March and in July (Fig. 1). From January to March, asparagus is usually not emerging and there is a rise in RFC from December to March just before spear emergence, which occurs about mid-March. During this 4-month period, RFC was significantly lower in summer-forced asparagus than spring-harvested or unharvested plants. In late March in all CP treatments and control, RFC decreased sharply. For unharvested asparagus, 3 months were required

for the RFC to again reach preemergence RFC in March. The requirement of a 3-month period for restoration of RFC levels after harvest to pre-harvest levels has been reported by Shelton and Lacy (1980), Scott et al. (1939), Downton and Torokfalvy (1975), and Lin and Hung (1978). RFC in spring-harvested asparagus did not return to preemergence RFC levels before the 1 Aug. fern removal; however, summer-forced asparagus reached preemergence RFC by fern removal in August. It is thought that August fern mowing removed aged fern of unharvested and spring-harvested plants and rejuvenated these plants. By December, fern is usually senescent and RFC returned to preemergence RFC levels in March for unharvested plants, spring- and summer-harvested plants. Shelton and Lacy (1980) in Michigan showed a similar trend in two RFC peaks during the growing season, with one before and after the harvest season; since the climate is so much different in the north temperate zones, the months of peak RFC in their study do not coincide with those in coastal South Carolina.

RFC in summer-forced asparagus was significantly less than spring-harvested in 10 out of 12 months but similar in July and significantly higher in December (Fig. 1). RFC in spring-harvested asparagus was similar to unharvested asparagus in February, March,

Table 7. Interaction of harvest duration and year on root fructose of spring-harvested, summer-forced asparagus from 1999 to 2002.

Cutting pressure	Fructose (mg·g ⁻¹ dry root wt)			
	1999	2000	2001	2002
Control	289 g ^z	362 bc	446 a	442 a
Low	298 fg	365 bc	382 b	378 b
Medium	320 ef	320 ef	380 b	363 bc
High	308 efg	334 de	362 bc	348 cd

^zMean pooled over harvest seasons within rows and columns are significantly different by LSD $P = 0.05$.

Table 8. Sources of variation in the analysis of variance for the effects of harvest year, season, growth stage and harvest duration and their interactions on the total variation in root carbohydrates from 1999 to 2003.

Source of variation ^z	Fructose (mg·g ⁻¹ root dry wt)
Replication	<1
Growth stage (GS)	10***
Year (Y)	12***
GS × Y	12***
Season (S)	1***
S × GS	<1
S × Y	<1
S × GS × Y	<1
Cutting pressure (CP)	1*
CP × GS	<1
CP × Y	<1
CP × GS × Y	<1
CP × S	<1
CP × S × GS	<1
CP × S × Y	<1
CP × S × GS × Y	<1
Error	53

^zSum of squares for each factor in the ANOVA converted to a percentage of total sum of squares.

***Significant at $P = 0.05$ and 0.001 .

April, November, and December; however, in all other sample months, spring-harvested RFC were significantly lower than RFC of unharvested control plants. The absolute lowest RFC for spring-harvested asparagus occurred in September and lowest RFC for summer-forced asparagus occurred in October.

The effect of CP on RFC changed over the harvest years progressively, with increasing harvest pressure decreasing RFC over time (Table 7). In the first harvest year in 1999, RFC were similar at all CP with medium CP tending to have the greatest RFC and high CP equivalent to the other CP even the control. In the second harvest year, the influence of CP was becoming more apparent since RFC were greater in the low CP and unharvested control compared to the medium and high CP. In the third harvest year, the influence of harvest pressure became stronger since RFC was similar among all CP but significantly greatest in the unharvested controls. By the last harvest year, as harvest pressure increased, RFC progressively decreased; RFC was greatest in the unharvested control, similar in low and medium CP plants, but lowest in the highest CP. Mean RFC in all CP increased yearly from 1999 to 2001 and plateaued from 2001 to 2002. From 1999 to 2002, RFC increased 53%, 27%, 13%, and 13% in unharvested control, and low, medium, and high CP, respectively, indicating that as CP increased, RFC decreased progressively.

Carbohydrate data was grouped into four significant asparagus growth stages to more accurately discern RFC dynamics in relation

to plant developmental status. The majority of variation (34%) in RFC was attributed to the collective effects of main effects of growth stage and harvest year and their interaction (Table 8). The main effects of season and CP together accounted for 2% of the variation in RFC and were considered minor and negligible. During 1999, the RFC was greatest during the preemergence/late dormancy stage (stage 1) just before the first harvest began in this study as expected (Fig. 2). Ideally, RFC should return to its greatest content just before harvest begins to sustain spring spear emergence and fern development that follows in stage 2, however, this was not the case. The RFC in this new asparagus planting did not recover again to this stage 1 level (1999) until late 2000 (stage 4). In the preemergence/late dormancy stage in 2000 (stage 1), the RFC was very low before entering into the spear production/fern development stage (stage 2); however, by stage 4 in 2000, RFC had recovered to a high and adequate level. For summer forcing to be successful, RFC content should replenish to high levels before summer forcing in stage 3 (fern rotation/summer rejuvenation stage). From 1999 to 2001, RFC recovered after summer forcing or fern rotation in spring-harvested plots; however, in 2002, the recovery was very inferior and at a significantly low RFC status in all harvest treatments except the unharvested controls. The low RFC status in 2002 during fern rotation/rejuvenation stage and the inferior recovery of RFC during autumnal senescence stage indicated lower crown vigor

and explained the increased production of culls in summer-forced asparagus. By 2003, inadequate crown vigor and RFC induced by the previous four harvest years had seriously weakened both spring-harvested plants, but especially summer-forced plants. As indicated by Paschold et al. (2002), rather than increasing CP with plant age, lower CP should be used with older plants to avoid a collective loss of vigor after many harvest years. It is suggested that rather than increasing CP with age, it may be necessary to keep CP the same over harvest years to reduce the stress that may reduce the potential of a plant to produce an adequate supply of quality sized spears.

The appropriate severity of CP for asparagus must be devised to 1) insure profitability for the grower and 2) encourage the longevity of this perennial crop. Using high CP requires additional labor costs and any yield increases with high CP must be factored into the decision-making planning and must be warranted by greater net income. In general, using medium and high CP increased marketable yield 16% and 22% in spring and summer, respectively (Table 5). Viewed over time, however, medium and high CP in spring or summer, produced statistically similar yields in the first 2 harvest years, significantly more in the third year, but in the fourth year, there was no significant advantage for higher CP (Table 4). Examination of yields from year to year indicated numerically greater yields but not significantly greater yields with the highest CP and these trends should not be ignored because of stringent statistical tests at the 95% confidence level. This outcome suggested that in future work, CP scenarios need to be evaluated not only increasing with crop age, but also decreasing with age as suggested by Paschold et al. (2002).

Based on the current study, we suggest that the highest CP scheme is appropriate for spring-harvested asparagus based on greatest marketable yields, acceptable RFC and cull

Fig. 2. Interaction of harvest year, growth stage and harvest season on root fructose of spring-harvested and summer-forced asparagus from 1999–2003 (1 = preemergence/late dormancy; 2 = spear production/fern development; 3 = fern rotation/summer rejuvenation; and 4 = autumnal senescence).

losses. For summer-forced asparagus, however, the lowest CP scheme is more appropriate based on acceptable marketable yields. High CP should not be used in summer forcing in order to avoid undue plant stress signified by the lowest RFC of all treatments which caused unacceptably large cull losses, mostly attributed to spindly spear size.

Literature Cited

- Cook, W. 1992. Asparagus weed and disease control. Agricultural chemical handbook. Clemson Univ. Coop. Ext. Serv. EC 670.
- Culpepper, C. and H. Moon. 1939. Effect of temperature upon the rate of elongation of the stems of asparagus grown under field conditions. *Plant Physiol.* 14: 667-698.
- Downton, W.J. and E. Torokfalvy. 1975. Photosynthesis in developing asparagus plants. *Austral. J. Plant Physiol.* 2:367-375.
- Dufault, R.J. 1994. Impact of forcing summer asparagus in coastal South Carolina on yield, quality, and recovery from harvest pressure. *J. Amer. Soc. Hort. Sci.* 119:396-402.
- Dufault, R.J. 1995. Harvest pressures affect forced summer asparagus yield in coastal South Carolina. *J. Amer. Soc. Hort. Sci.* 120:14-20.
- Dufault, R.J. 1999. Mother stalk culture does not improve plant survival or yield of spring and summer-forced asparagus in South Carolina. *HortScience* 34(2): 225-228.
- Hung, L. 1980. Special aspect of asparagus growing in Taiwan. *J. Chinese Soc. Hort. Sci.* 26(1):1-10.
- Lin, A.C. and L. Hung. 1978. A study on photosynthesis of asparagus. *Mem. Col. Agr. Nat. Taiwan Univ.* 18(1):88-95.
- Paschold, P., B. Artelt, and G. Herman. 2002. Influence of harvest duration on yield and quality of asparagus. *Acta Hort.* 589:65-68.
- Scott, L.E., J.H. Mitchell, and R.A. McGinty. 1939. Effects of certain treatments on the carbohydrate reserves of asparagus crowns. *South Carolina Agr. Expt. Sta. Bul.* 321.
- Shelton, D.R. and M.L. Lacy. 1980. Effect of harvest duration on yield and on depletion of storage carbohydrates in asparagus roots. *J. Amer. Soc. Hort. Sci.* 105:332-335.
- U.S. Department of Agriculture. 1977. United States standards for grades of fresh asparagus. U.S. Dept. Agr. Food Safety Qual. Serv., Wash., D.C.
- Wang, C.S. 1965. A preliminary report on mother stalk method of harvesting asparagus. *J. Chinese Soc. Hort. Sci.* 11(3/4):100-105.
- Williams, J. And J. Garthwaite. 1973) The effects of seed and crown size and length of cutting period on the yield and quality of asparagus grown on ridges. *Expt. Hort.* 25:77-86.
- Wilson, D.R., S.M. Sinton, and C.E. Wright. 1999. Influence of time of spear harvest on root systems resources during the growth cycle of asparagus. *Acta Hort.* 479:313-320.