3 Results

Pretreatment Measurements

Milfoil

Pretreatment measurements of 4- and 8-week-old milfoil test plants are compared in Figure 3. Dominant shoot length (Figure 3a) of test plants was statistically different ($F = 11.27$, $p = 0.0001$) among culture tanks, with mean comparisons tests indicating that dominant shoots from each of the 8-week culture tanks were longer than dominant shoots from each of the 4-week culture tanks. Significant differences ($F = 69.28$, $p = 0.0001$) were also detected in shoot length for data pooled by age group. Dominant shoot biomass (Figure 3c) was more variable among culture tanks, with differences being only slightly significant ($F = 2.10$, $p = 0.0495$). However, when pooled by age group, 8-week-old dominant shoots had significantly more biomass than 4-week-old shoots ($F = 11.23$, $p = 0.0011$). Meristems per dominant shoot were significantly different among culture tanks ($F = 3.83$, $p = 0.0009$), but differences in pooled data by age group were not significant ($F = 1.16$, $p = 0.284$). In addition to significantly larger dominant shoots in 8-week cultures, 8-week cultures were also observed to have more shoots per flat. When pooled by age group, total flat biomass was significantly higher for 8-week plants than for 4-week plants (Figure 3d) ($F = 10.05$, $p = 0.0193$).

Shoot-breaking forces and tensile strengths of milfoil test plants are compared in Figure 4. Significant differences in shoot-breaking forces were detected ($F = 78.84$, $p = 0.0001$) among different shoot sections (Zone 1-Zone 3) and age groups. For both age groups, breaking forces were significantly higher toward the base of the shoots (Zone 1). Differences in breaking forces were partially explained by differences in shoot diameter, which were observed to be greater in basal sections of the shoots, and with basal sections of 8-week-old shoots being greater than 4-week-old shoots. However, since tensile strength measurements

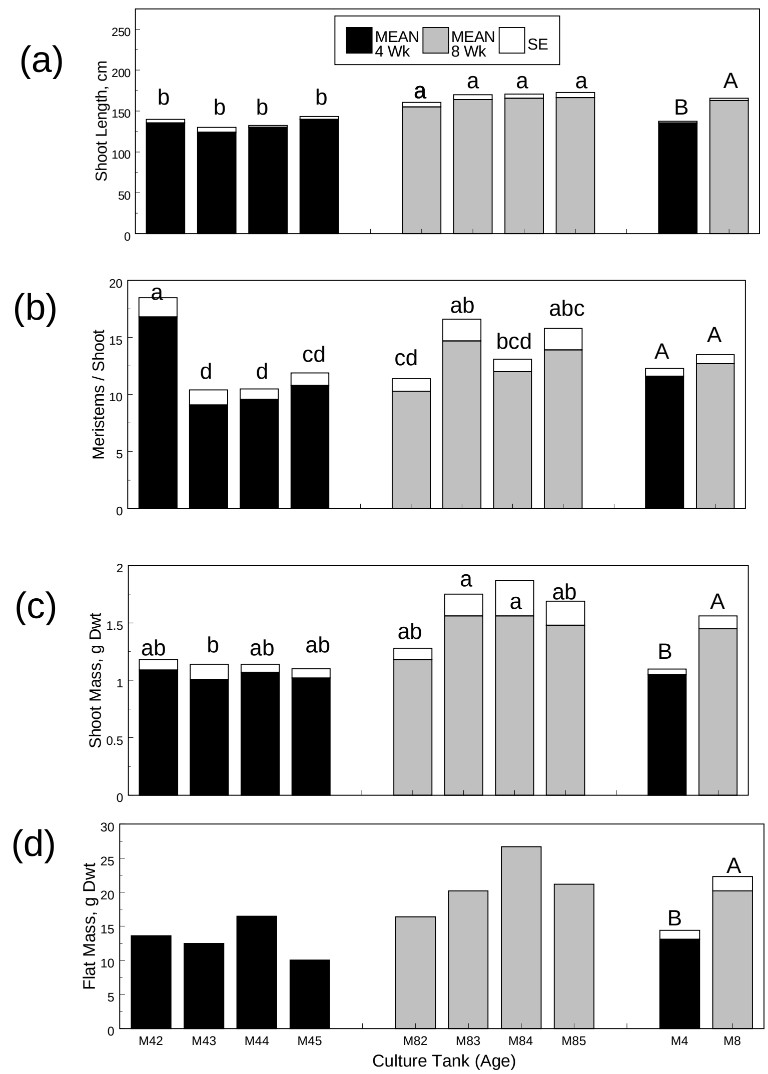

Figure 3. Pretreatment measurements for Eurasian watermilfoil plants: (a) shoot length, (b) meristems/shoot, (c) shoot biomass, (d) total flat biomass. Labels on x-axis indicate culture tank and, therefore, distinguish species and age. Letters above bars show results of means separation tests using Fisher'' least significant difference (LSD) procedure (p = 0.05)

(Figure 4b), which correct for differences in shoot diameter, were also significantly different between age and shoot zone ($F = 11.22$, $p = 0.0001$), factors in addition to shoot diameter were apparently involved.

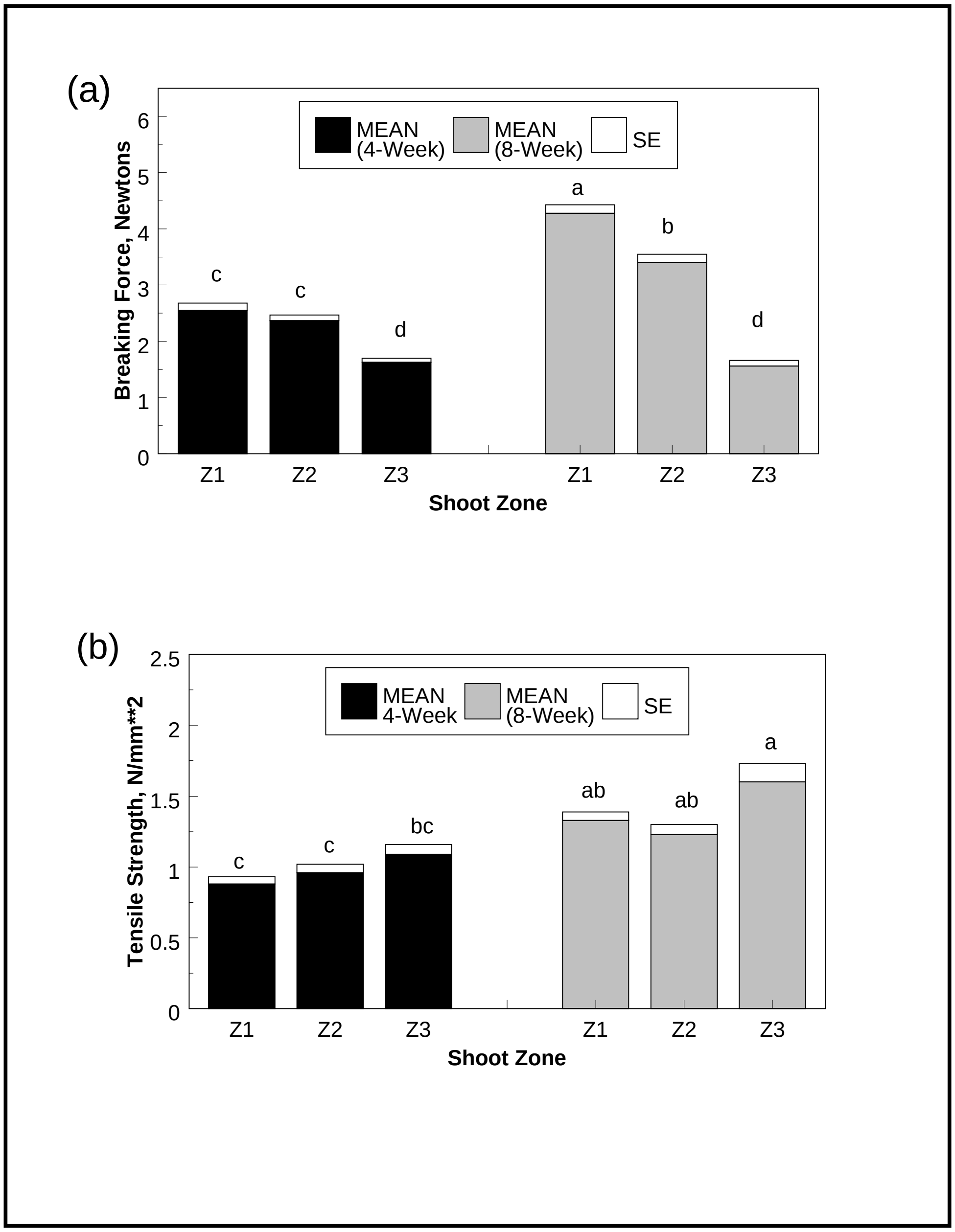

Figure 4. Eurasian watermilfoil shoots: (a) breaking forces and (b) tensile strengths. (Labels on x-axis indicate shoot zones: Z1 = basal section, Z2 = midsection, Z3 = apical section. Letters above bars show results of means separation tests using Fisher's LSD procedure (p = 0.05))

Vallisneria

Mean values for pretreatment growth parameters of vallisneria test plants are shown in Figure 5. Longest leaf measurements (Figure 5a) of dominant shoots were statistically different across culture tanks and age groups (F = 46.68, p = 0.0001). When pooled by age, 8-week dominant shoots had significantly longer leaves than did 4-week shoots (F = 247.4, p = 0.0001). Significant differences (F = 3.68, p = 0.0013) were also detected in the number of leaves per dominant shoot among the culture tanks (Figure 5b). However, when pooled by age group, number of leaves per dominant shoot were shown to be statistically similar (F = 0.63, p = 0.429). Dominant shoot biomass (Figure 5c) was significantly different among the culture tanks (F = 30.27, p = 0.0001), with 8-week-old shoots having consistently higher biomass than 4-week-old shoots. Pooled shoot biomass data also detected this difference between age groups (F = 145.4, p = 0.0001). As for milfoil, overall flat biomass was significantly higher in 8-week test cultures than in 4-week test cultures (F = 57.2, p = 0.0003) (Figure 5d).

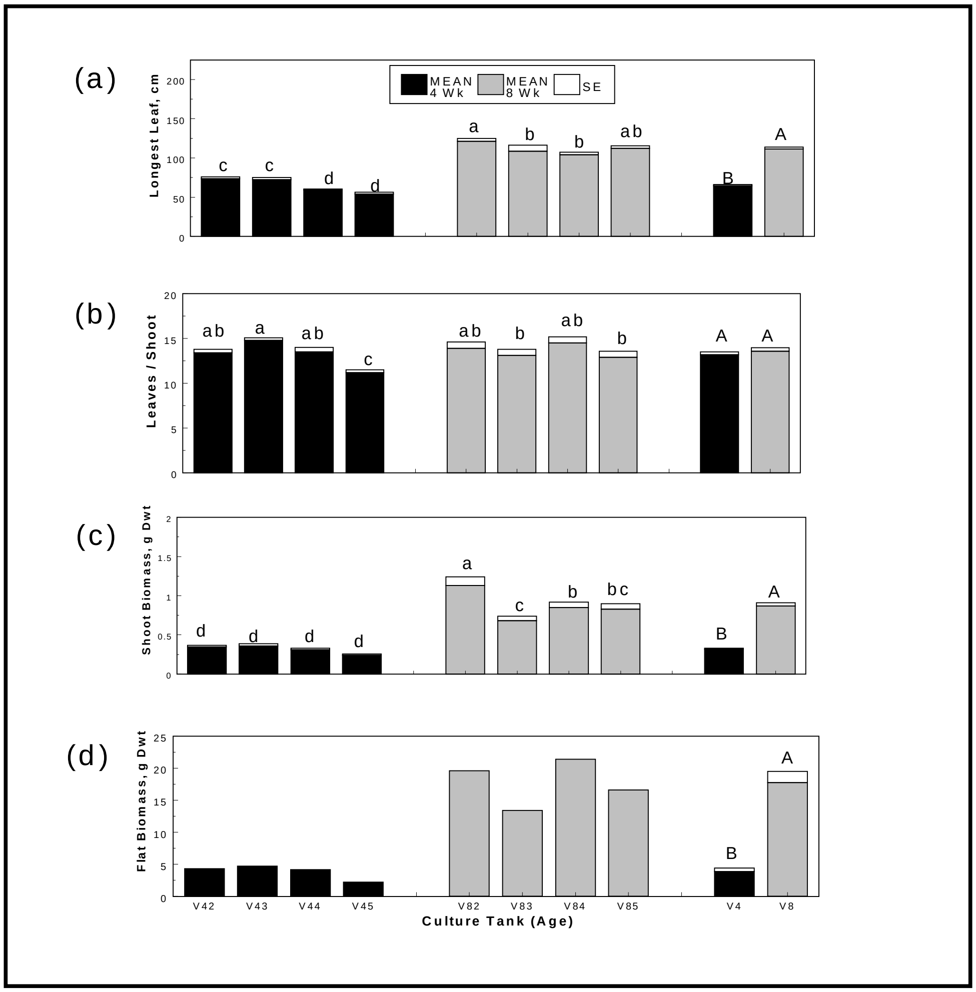

Figure 5 Pretreatment measurements for vallisneria plants. (Labels on x-axis indicate culture tanks and, therefore, distinguish species and age. Letters above bars show results of means separation tests using Fisher's LSD procedure (p = 0.05))

Four-week-old test plants had not begun to develop flowers, while 8-week test plants had a mean of 2.92 flower pedicels per dominant shoot. Overall mean pedicel length was 109.4 cm. Mean force to break flower pedicels and their mean tensile strengths are shown for the 8-week-old culture tanks in Figure 6a. Significant differences ($F = 14.39$, $p = 0.0001$) detected in pedicel breaking forces among the different culture tanks were due to the significantly higher force requirements for pedicels in the V82 culture tank. Statistical differences were not detected in pedicel tensile strengths among the different culture tanks ($F = 0.36$, $p = 0.783$) (Figure 6b), indicating that the higher breaking force of pedicels from the V82 culture tank was a result of greater pedicel diameter.

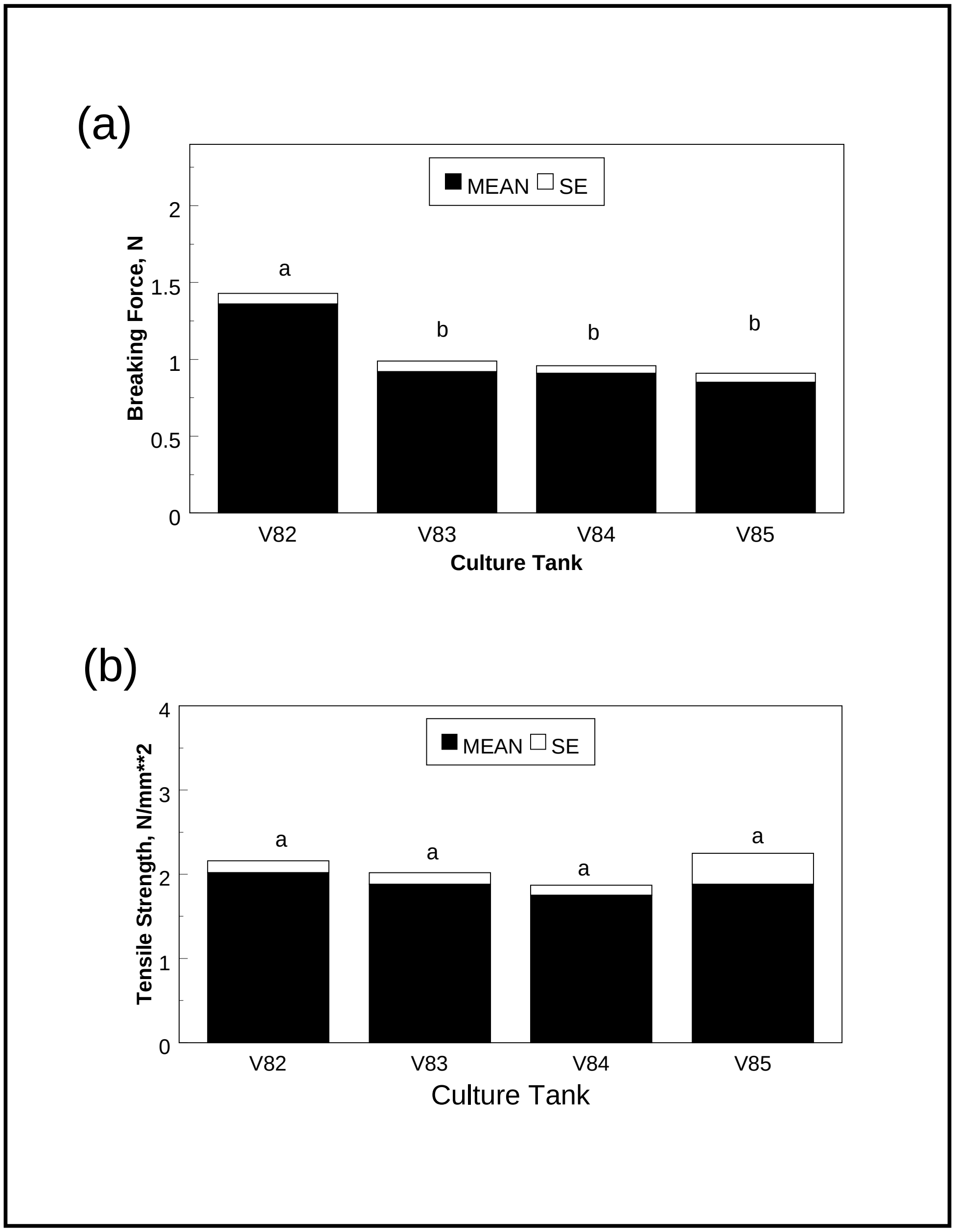

Figure 6. Breaking forces of vallisneria leaves and tensile strengths of vallisneria flower pedicels. (Letters above bars show results of means separation tests using Fisher's LSD procedure ($p = 0.05$))

Damage to Milfoil Plants (Treatment Comparisons)

Cumulative fragment numbers

Mean values for the cumulative number of fragments broken from milfoil plants by each of the hydrological treatments are given in Table 3. Data in the table were analyzed separately by plant age.

Table 3
Cumulative Numbers[1] of Fragments Broken from Eurasian Water-mifoil Plants Exposed to Each of the Hydrological Treatments

Plant Age, Weeks	Current Velocity m/sec	Wave Period = 3 sec			Wave Period = 5 sec		
		Wave Height, m			Wave Height, m		
		0.1	0.2	0.3	0.1	0.2	0.3
4 WEEKS	0.25	8.67 b-e[2] • 2.404[3] (T1)[4]	14.00 abc • 4.726 (T2)	22.33 a • 6.119 (T3)	1.67 def • 0.882 (T4)	9.00 bed • 2.000 (T5)	13.00 bc • 3.005 (T6)
	0.10	NR[5] (T7)	NR (T8)	NR (T9)	3.00 def • 1.000 (T10)	7.00 c-f • 2.517 (T11)	15.67 ab • 4.978 (T12)
	0.00	0.33 ef • 0.333 (T13)	0.67 def • 0.333 (T14)	12.33 bc • 4.055 (T15)	0.00 f • 0.000 (T16)	0.33 ef • 0.333 (T17)	2.33 def • 0.882 (T18)
8 WEEKS	0.25	12.00 def • 3.215 (T1)	14.00 def • 4.933 (T2)	16.67 def • 4.410 (T3)	3.67 f • 0.882 (T4)	8.67 def • 2.404 (T5)	10.67 def • 3.180 (T6)
	0.10	8.67 def • 3.283 (T7)	23.33 cd • 4.333 (T8)	31.67 bc • 5.696 (T9)	12.33 def • 2.333 (T10)	22.33 cde • 4.333 (T11)	38.67 b • 4.807 (T12)
	0.00	8.67 def • 3.930 (T13)	21.33 cde • 8.452 (T14)	55.00 a • 12.767 (T15)	2.00 f • 0.577 (T16)	8.33 ef • 1.764 (T17)	34.00 bc • 7.572 (T18)

[1] Based on assumptions of the experimental design, fragment numbers were summed through the series of wave height exposures. Numeric values are means • standard errors (n = 3). Treatment results for the two age groups were analyzed separately by ANOVA: 4-week-old plants ($F = 5.91$, $p = 0.0001$), 8-week-old plants ($F = 6.75$, $p = 0.0001$).
[2] Means comparisons among different treatments were conducted separately for the two age groups by Fisher• s LSD test, with significant differences not detected ($p = 0.05$) between means having the same letter (4-week LSD = 8.371; 8-week LSD = 14.815).
[3] Values are standard errors of the means.
[4] Treatment numbers are in parentheses (T1 = Treatment 1, T2 = Treatment 2, etc.)
[5] NR = not run.

For 4-week-old plants, Treatment 3 (referred to as T3 in Table 3), which had wave heights of 0.3 m, a 3-sec wave period, and a current velocity of 0.25 m/sec, was the most damaging treatment. Other treatments which produced statistically similar fragment numbers were Treatment 2 (T2) and Treatment 12 (T12). Though high variability and small sample sizes (n = 3) make it difficult to compare treatment effects, the data tend to indicate that under the high current velocities, irregardless of wave period, similar numbers of fragments were generated by each of the three treatments in a given series of the three wave height exposures. In comparison, under the lower current velocity, no significant damage was generated by wave heights less than 0.3 m. For example, Treatments 13 and 14 (T13 and T14, respectively) generated essentially no fragments, while Treatment 15 (T15), the 0.3-m wave height exposure in that series, generated 12.33 fragments.

For 8-week-old plants, fragment production under the 0.25-m/sec treatment series appears similar to the damage to 4-week-old plants by these treatments. In these treatment series (T1-T3 and T4-T6), damage was again initiated at the 0.1-m wave height treatments, and cumulative fragment numbers after the 0.3-m wave height exposures were near those for 4-week-old plants, though they were not compared statistically. For the two treatment series at 0.1-m/sec, fragment production was similar at each wave height, resulting in a linear accumulation of fragments. Cumulative fragment numbers after the 0.3-m wave height exposures at the intermediate current velocity (0.10 m/sec) were higher than those numbers produced by the high current velocity (0.25-m/sec) treatments. Highest cumulative numbers of fragments were generated by the series of 3-sec waves with no current 0.0 m/sec (T13-T15). The majority of fragments generated by this series of treatments, as well as the majority of fragments generated by the other no current (0.00 m/sec) treatment series (T16-T18), were produced during the 0.3-m wave height exposure. Instead of the near linear accumulation of fragments at each wave height exposure as occurred during the 0.10 m/sec series, the 0.3-m wave height treatments of the 0.00 m/sec series produced two- to three-fold more fragments than had been accumulated during exposures to the two lower wave height treatments.

Cumulative fragment biomass

In terms of biomass losses, the series of treatments to long period waves at the high current velocity (T4-T6) was the most damaging to 4-week-old plants, producing a cumulative total of 0.86-grams dry weight biomass (g dwt) after the 0.2-m wave height exposure and 1.49-g dwt biomass after the 0.3-m wave height exposure (Table 4). The next most damaging treatments were the series of 5-sec waves at the intermediate current velocity (T10-T12) and the series of 3-sec waves at no current (T13-T15). Though these latter two series of treatments produced similar cumulative losses, comparison of the cumulative losses after the 0.2-m wave height exposures (i.e., T11 versus T14) indicates that this intermediate wave height was more damaging in the 0.10 m/sec treatment series than in the 0.0 m/sec treatment series. Similarly, exposures to long period waves with heights less than 0.3 m (T16 and T17) were also not damaging.

Table 4
Cumulative Biomass (g Dwt)[1] of Fragments Broken from Eurasian Watermifoil Plants Exposed to Each of the Hydrological Treatments

Plant Age, Weeks	Current Velocity m/sec	Wave Period = 3 sec			Wave Period = 5 sec		
		Wave Height, m			Wave Height, m		
		0.1	0.2	0.3	0.1	0.2	0.3
4 WEEKS	0.25	0.23 def[2] ±0.059[3] (T1)[4]	0.35 e-f ±0.097 (T2)	0.73 b-e ±0.283 (T3)	0.17 ef ±0.140 (T4)	0.86 a-d ±0.139 (T5)	1.49 a ±0.304 (T6)
	0.10	NR[5] (T7)	NR (T8)	NR (T9)	0.09 ef ±0.020 (T10)	0.53 b-f ±0.390 (T11)	1.02 ab ±0.402 (T12)
	0.00	0.01 f ±0.009 (T13)	0.02 f ±0.021 (T14)	0.90 abc ±0.386 (T15)	0.00 f ±0.000 (T16)	0.01 f ±0.012 (T17)	0.49 b-f ±0.330 (T18)
8 WEEKS	0.25	0.84 de ±0.306 (T1)	0.95 de ±0.404 (T2)	1.30 cde ±0.335 (T3)	0.10 e ±0.035 (T4)	0.39 de ±0.144 (T5)	0.43 de ±0.155 (T6)
	0.10	2.18 b-e ±1.458 (T7)	5.01 ab ±2.465 (T8)	6.25 a ±2.617 (T9)	0.46 de ±0.086 (T10)	1.42 cde ±0.409 (T11)	2.49 b-e ±0.779 (T12)
	0.00	0.54 de ±0.202 (T13)	1.56 cde ±0.371 (T14)	4.16 abc ±1.328 (T15)	0.10 e ±0.059 (T16)	0.63 de ±0.374 (T17)	3.01 bcd ±0.938 (T18)

[1] Based on assumptions of the experimental design, fragment mass was summed through the series of wave height exposures. Numeric values are means ± standard errors (n = 3). Treatment results for the two age groups were analyzed separately by ANOVA: 4-week-old plants ($F = 6.46$, $p = 0.0001$), 8-week-old plants ($F = 3.02$, $p = 0.0021$).
[2] Means comparisons among different treatments were conducted separately for the two age groups by Fisher's LSD test, with significant differences not detected ($p = 0.05$) between means having the same letter (4-week LSD = 0.6494; 8-week LSD = 2.885).
[3] Values are standard errors of the means.
[4] Treatment numbers are in parentheses (T1 = Treatment 1, T2 = Treatment 2, etc.)
[5] NR = not run.

Cumulative biomass loss from 8-week-old plants was significantly higher in the series of treatments (T7-T10) with short wave periods and the intermediate current velocity (Table 4). Consistent with cumulative fragment numbers, biomass losses were significantly higher in treatments with intermediate and low current velocities than in treatments with high current velocities.

Damage to Vallisneria Plants (Treatment Comparisons)

Cumulative fragment numbers

None of the hydrological treatments with a 0.25-m/sec current velocity produced fragment numbers significantly greater than zero in either 4- or 8-week-old plants (Table 5). In the intermediate and no-current treatment series (i.e., 0.1 and 0.0 m/sec, respectively) of 4-week-old plants, cumulative numbers of fragments were significantly greater than zero following the 0.3-m wave height exposure of the series (i.e., T12, T15, and T18). In the zero current and short (3 sec)

Table 5
Cumulative Numbers[1] of Fragments Broken from Vallisneria Plants Exposed to Each of the Hydrological Treatments

Plant Age, Weeks	Current Velocity m/sec	Wave Period = 3 sec			Wave Period = 5 sec		
		Wave Height, m			Wave Height, m		
		0.1	0.2	0.3	0.1	0.2	0.3
4 WEEKS	0.25	1.67 d[2] ±1.667[3] (T1)[4]	2.67 d ±1.764 (T2)	3.33 d ±2.404 (T3)	0.33 d ±0.333 (T4)	0.33 d ±0.333 (T5)	0.33 d ±0.333 (T6)
	0.10	NR[5] (T7)	NR (T8)	NR (T9)	0.33 d ±0.333 (T10)	3.67 d ±1.202 (T11)	10.00 c ±3.055 (T12)
	0.00	2.67 d ±1.333 (T13)	10.33 bc ±3.480 (T14)	19.33 a ±4.333 (T15)	0.33 d ±0.333 (T16)	4.33 cd ±2.028 (T17)	16.33 ab ±3.756 (T18)
8 WEEKS	0.25	2.67 fg ±0.882 (T1)	5.67 efg ±2.603 (T2)	9.33 d-g ±3.712 (T3)	0.67 g ±0.667 (T4)	2.67 fg ±1.667 (T5)	6.67 d-g ±2.667 (T6)
	0.10	4.33 fg ±1.202 (T7)	12.33 d-g ±4.702 (T8)	25.33 ab ±5.783 (T9)	9.67 d-g ±0.333 (T10)	26.33 ab ±3.528 (T11)	36.00 a ±5.132 (T12)
	0.00	5.67 efg ±2.848 (T13)	18.33 bcd ±6.227 (T14)	36.67 a ±6.173 (T15)	1.00 g ±0.577 (T16)	16.67 b-e ±2.404 (T17)	37.00 a ±8.718 (T18)

[1] Based on assumptions of the experimental design, fragment numbers were summed through the series of wave height exposures. Numeric values are means ± standard errors (n = 3). Treatment results for the two age groups were analyzed separately by ANOVA: 4-week-old plants (F = 7.78, p > F = 0.0001), 8-week-old plants (F = 9.21, p > F = 0.0001).
[2] Means comparisons among different treatments were conducted separately for the two age groups by Fisher's LSD test, with significant differences not detected (p = 0.05) between means having the same letter (4-week LSD = 6.19; 8-week LSD = 11.69).
[3] Values are standard errors of the means.
[4] Treatment numbers are in parentheses (T1 = Treatment 1, T2 = Treatment 2, etc.)
[5] NR = not run.

wave period treatment series (i.e., T13-T15), significant cumulative numbers of fragments had been collected from 4-week-old plants following the 0.2-m wave height exposure (i.e., T14). Similar trends, but with higher fragment numbers, were observed for 8-week plant exposures, with the exception being that the 0.2-m wave height treatments generated significant numbers of fragments in all but one of these treatment series (i.e., T7-T9).

Cumulative fragment biomass

Significant biomass losses to 4-week-old vallisneria plants were only generated by the two treatment series with no current (Table 6). In these series, both the 0.2-m and the 0.3-m wave heights generated significant damage in the short (3 sec) wave period series (i.e., T13-T15), while only the 0.3-m waves generated significant damage in the long (5 sec) wave period series (T16-T18). In comparison, 8-week-old plants suffered significant biomass losses under the two hydrological treatment series with no current as well as the two treatment series with an intermediate current (Table 6). As with cumulative fragment numbers, biomass losses resulting from the treatments were higher for 8-week-old plants than for 4-week-old plants.

Species, Age, and Wave Period Effects

Cumulative fragment numbers and biomass following the 0.3-m wave height treatments were analyzed separately by current velocity settings (i.e., 0.25 m/sec, 0.10 m/sec, 0.00 m/sec) to provide further clarification of the effects that plant species, plant age, and wave period setting had on the amount of cumulative damage resulting from the sequential exposures to the three wave heights. These analyses were considered necessary since preliminary tests indicated that species and age were significant factors in all comparisons, and that wave period was significant in all comparisons except for numbers of vallisneria fragments.

Cumulative fragment numbers and types

Cumulative numbers of fragments generated under treatment series incorporating each of the three current velocity settings are shown in Figure 7. Overall analysis of cumulative fragment numbers resulting from the 0.25-m/sec treatment series (Figure 7a) showed a significant treatment effect ($F = 3.93$, $p = 0.011$). In comparisons between the two species, cumulative fragment numbers were numerically higher for milfoil than for vallisneria. However, Fisher's LSD test detected significant differences only between 4-week-old plants, with 4-week-old milfoil plants incurring significantly higher fragment losses under both wave period settings. For vallisneria, numbers of fragments were higher from 8-week-old plants than from 4-week-old plants, but the means separation procedure did not detect significant differences at $p = 0.05$. The data similarly indicate that 3-sec wave periods consistently generated slightly more damage than 5-sec wave periods for treatments with same species and aged plants.

Table 6
Cumulative Biomass (g Dwt)[1] of Fragments Broken from Vallisneria Plants Exposed to Each of the Hydrological Treatments

Plant Age, Weeks	Current Velocity m/sec	Wave Period = 3 sec Wave Height, m 0.1	 0.2	 0.3	Wave Period = 5 sec Wave Height, m 0.1	 0.2	 0.3
4 WEEKS	0.25	0.02 c[2] ±0.018[3] (T1)[4]	0.025 c ±0.017 (T2)	0.028 c ±0.020 (T3)	0.000 c ±0.000 (T4)	0.000 c ±0.000 (T5)	0.000 c ±0.000 (T6)
	0.10	NR[5] (T7)	NR (T8)	NR (T9)	0.002 c ±0.002 (T10)	0.022 c ±0.003 (T11)	0.049 c ±0.010 (T12)
	0.00	0.029 c ±0.018 (T13)	0.125 b ±0.043 (T14)	0.242 a ±0.056 (T15)	0.001 c ±0.001 (T16)	0.035 c ±0.016 (T17)	0.131 b ±0.017 (T18)
8 WEEKS	0.25	0.043 fg ±0.013 (T1)	0.069 fg ±0.022 (T2)	0.097 efg ±0.036 (T3)	0.044 fg ±0.044 (T4)	0.071 fg ±0.063 (T5)	0.120 d-g ±0.060 (T6)
	0.10	0.056 fg ±0.026 (T7)	0.186 c-f ±0.077 (T8)	0.460 a ±0.125 (T9)	0.106 efg ±0.012 (T10)	0.321 abc ±0.058 (T11)	0.409 ab ±0.090 (T12)
	0.00	0.052 fg ±0.028 (T13)	0.279 bcd ±0.058 (T14)	0.379 ab ±0.090 (T15)	0.009 g ±0.009 (T16)	0.122 d-g ±0.028 (T17)	0.263 b-e ±0.058 (T18)

[1] Based on assumptions of the experimental design, fragment mass was summed through the series of wave height exposures. Numeric values are means ± standard errors (n = 3). Treatment results for the two age groups were analyzed separately by ANOVA: 4-week-old plants (F = 7.78, p = 0.0001), 8-week-old plants (F = 10.10, p = 0.0001).
[2] Means comparisons among different treatments were conducted separately for the two age groups by Fisher's LSD test, with significant differences not detected (p = 0.05) between means having the same letter (4-week LSD = 0.0623; 8-week LSD = 0.1688).
[3] Values are standard errors of the means.
[4] Treatment numbers are in parentheses (T1 = Treatment 1, T2 = Treatment 2, etc.)
[5] NR = not run.

Under treatments with a 0.10-m/sec current (Figure 7b), the effects of plant species, age, and wave period on cumulative fragment numbers were also shown to be significant (F = 5.26, p = 0.009). At this current velocity, means separation tests showed that 8-week-old plants had significantly more fragments than did 4-week-old plants. Differences between species and wave periods were less than under the higher current velocity and were statistically unimportant.

The effects of plant species, age, and wave period were also shown to be significant (F = 6.01, p = 0.002) under treatments with no ambient current (Figure 7c). Under these treatments, 8-week-old milfoil plants had significantly more fragments than did 4-week-old plants under both wave period settings. Though 8-

week-old vallisneria plants also had numerically larger numbers of fragments than 4-week-old plants, these differences were not shown to be significant by the means separation test. Similarly for vallisneria, no significant effect was detected for wave period. The cumulative numbers of fragments by fragment type for the individual treatment series are listed in Figure 8.

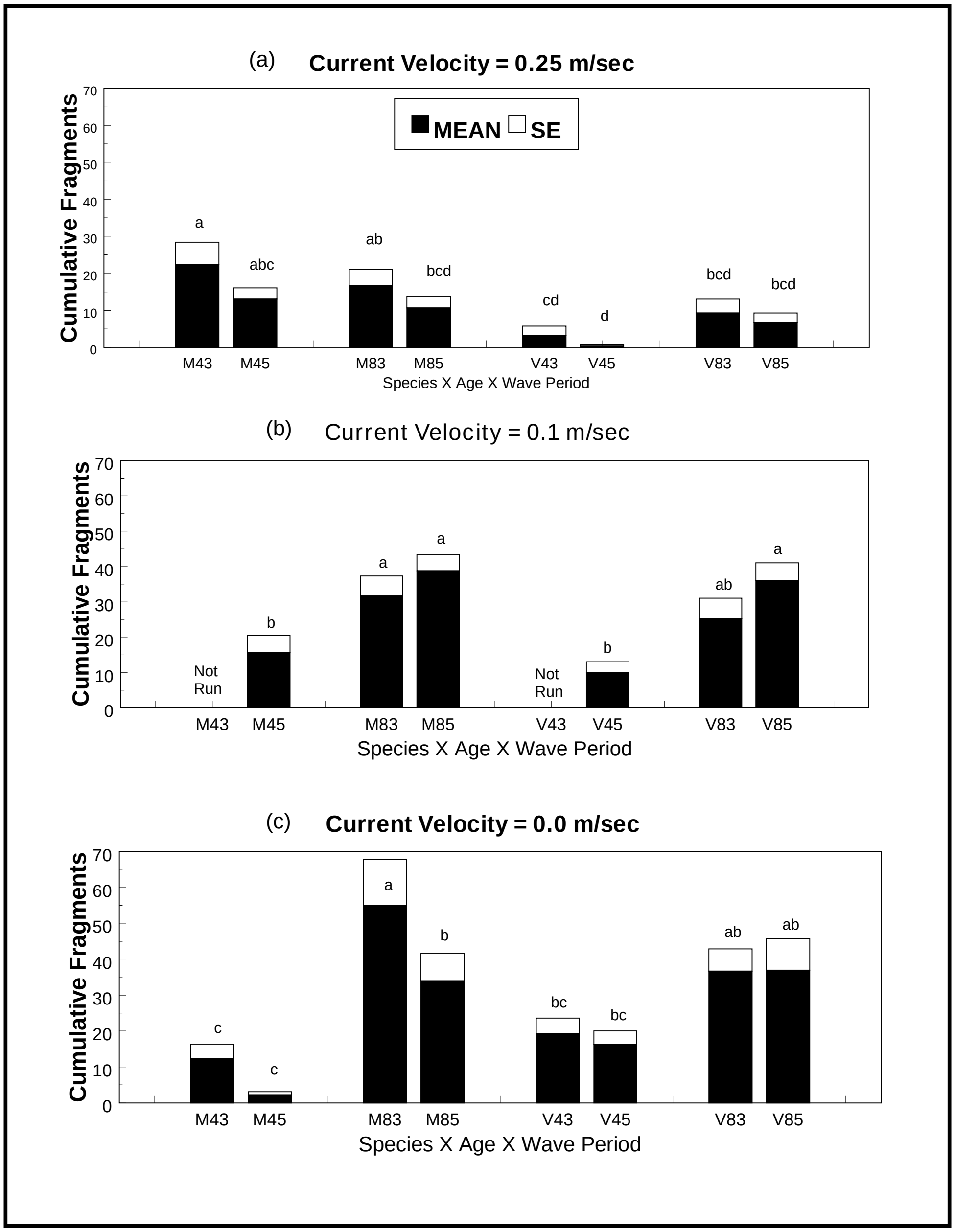

Figure 7 Cumulative numbers of fragments from the different species and age groups resulting from exposures to all three wave height settings under the three different current velocities. (Labels on x-axis indicate species, age (weeks), and wave period (sec). Letters above bars show results of mean separation tests using Fisher's LSD procedures (p = 0.05))

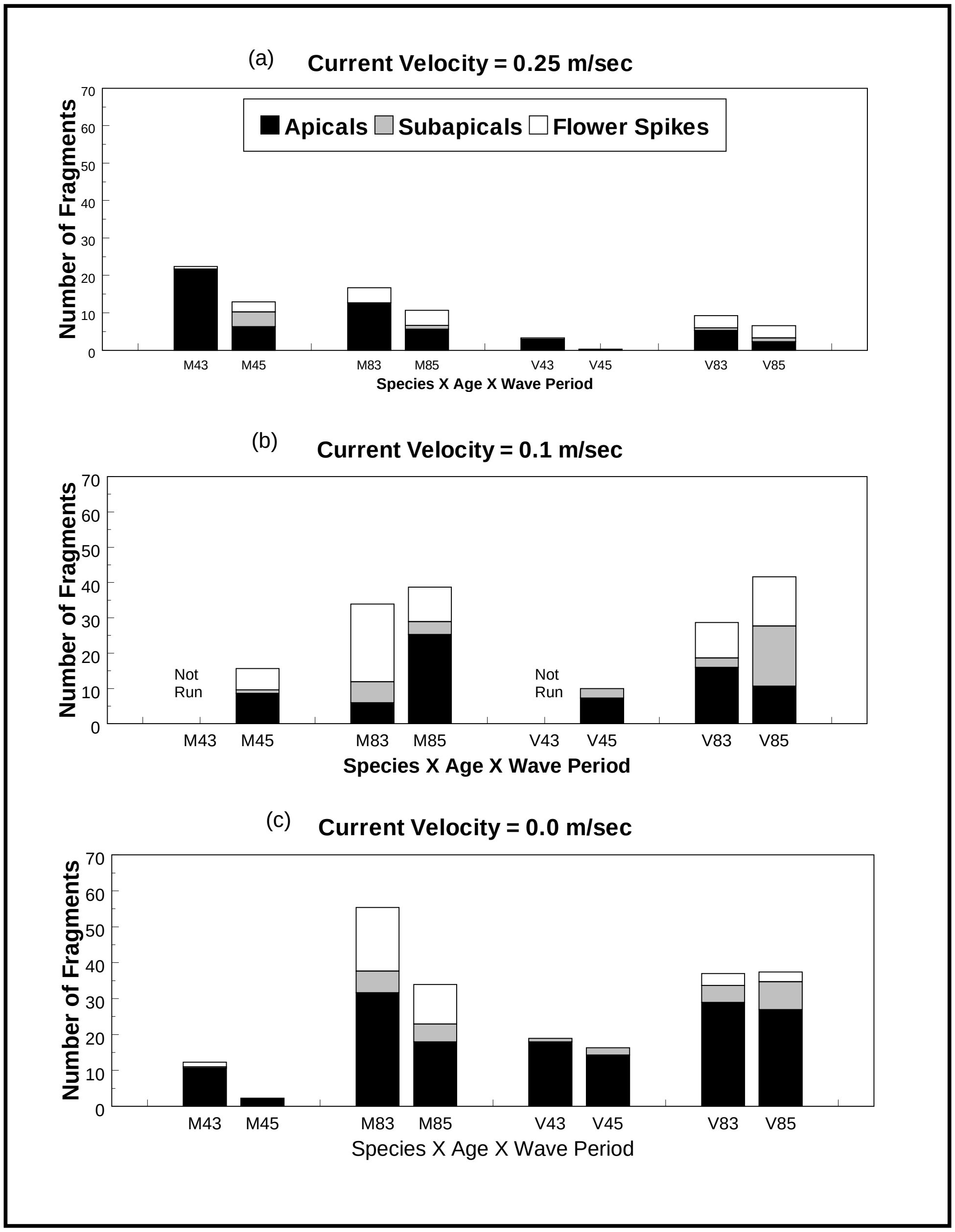

Figure 8. Cumulative numbers of fragments by fragment type for the individual treatment series. (Labels on x-axis indicate species, age (weeks), and wave period (sec))

Cumulative fragment biomass

Cumulative fragment biomass generated under each of the three current velocity settings for treatments incorporating the two plant species, ages, and wave period settings are shown in Figure 9. For the high current velocity treatments (Figure 9a), the overall ANOVA indicated that a highly significant difference existed in the amount of damage to groupings based on plant species, age, and wave period ($F = 8.90$, $p = 0.0002$). Means separations tests further clarified that significant differences existed in three of the four comparisons based on differences in plant species only, with milfoil generally losing more fragment biomass than vallisneria. For vallisneria, no effect of plant age or wave period was detected. For milfoil, significant differences were detected for age and wave period effects, but there was no consistent relationship based on these parameters.

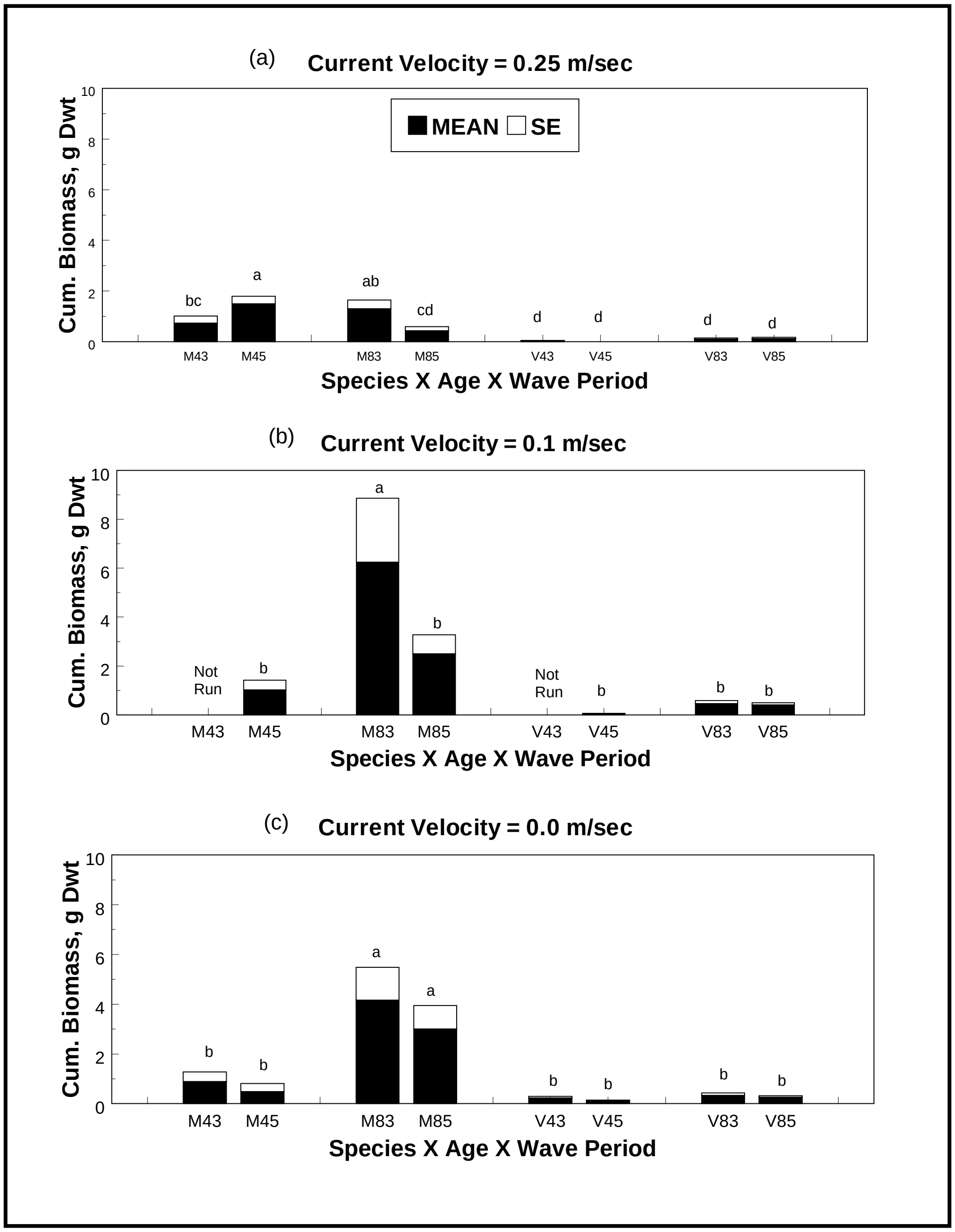

Figure 9. Cumulative biomass of fragments from the different species and age groups resulting from exposure to all three wave height settings under the three different current velocities. (Labels on x-axis indicate species, age (weeks), and wave period (sec). Letters above bars show results of means separation tests using Fisher's LSD procedure (p = 0.05))

For the intermediate 0.10-m/sec current velocity treatments (Figure 9b), a significant group effect was again detected (F = 4.35, p = 0.017). At this current velocity, 8-week-old milfoil plants exposed under the short (3 sec) wave period lost significantly more biomass than any of the other five groups. Differences between cumulative fragment biomass means for the other groups were not significant.

A significant group effect (F = 6.35, p = 0.001) was also detected for groups exposed to the no-current treatments (Figure 9c). As with intermediate current velocity treatments, means separation tests again indicated that the difference was the result of the significantly greater amount of biomass loss from 8-week-old milfoil plants. At this test current setting, however, 8-week-old milfoil losses were significantly higher under both wave period settings.

Observations of Test Plant Exposure to Waves

Wave damage to an object depends on the amount of energy within the wave that contacts the object and the ability of the object to withstand the wave energy. Most of the energy within a wave is generated by water circulation around the main wave orbit. The actual force generated within the wave orbit is a function of wave height, wave period, wavelength, and wave celerity (Denny 1988). Wave height not only affects wave force, but also determines how deeply into the water column the wave energy penetrates, with maximum wave forces penetrating to a still-water depth equal to one-half the wave height. Other forces generated by repeating waves are the result of countercurrents in the wave troughs between wave crests (Figure 10).

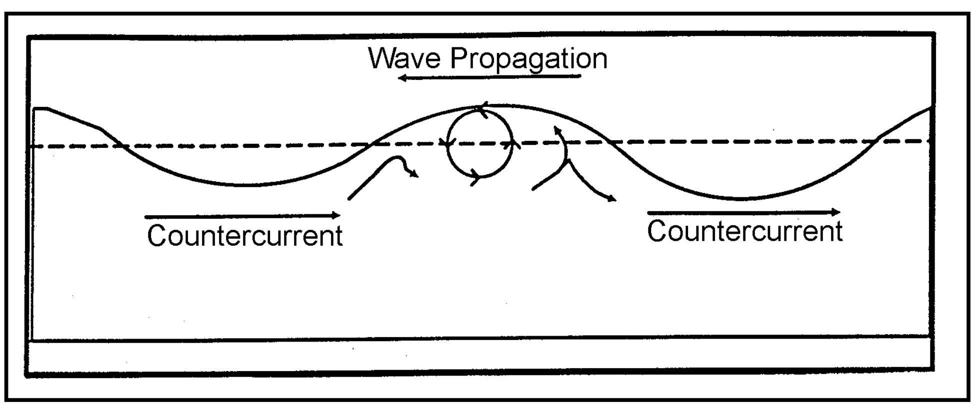

Figure 10. Illustration of the direction of main currents within a repeating wave series

Submersed aquatic plants used in this study are rooted, nonrigid objects whose exposure to wave forces is dependent on the following three factors:

a. The velocity and direction of the ambient current which, among other factors, determines the plant's orientation in relation to the approaching wave.

b. The length of the plant's shoots or leaves, which determines how high into the water column the shoot can extend.

c. The wave height, which determines the maximum depth of wave energy penetration, as well as the amount of wave energy.

Ambient current velocity effects

In all treatments, ambient currents were in the same direction as the direction of passing waves. Major differences in exposure to wave forces occurred as a result of how the ambient current oriented the shoots in relation to the approaching waves. As shown in Figure 11a , the 0.25-m/sec ambient current oriented the 8-week-old milfoil shoots at a 170-deg angle from the source of the approaching waves. This resulted in all of the shoot material being held below the water surface, with the apical tip being approximately 25 cm below the surface. At an ambient current velocity of 0.10 m/sec (Figure 11b), the resulting angle of orientation was reduced to 150 deg, and approximately 50 cm of the shoot apex was floating on the surface. Under treatments with no ambient current (Figure 11c), the angle of orientation was reduced to 90 deg, and two-thirds of the shoot material was on the water surface.

Due to differences in the angle of orientation to approaching waves resulting from the different ambient currents, the exposed plants encountered different wave energy exposures under the different treatments. These differences are visually compared for 0.3-m wave exposures in Figures 12-14, which provide illustrations of the movement patterns of 8-week-old milfoil plants under the three ambient current velocities.

For the high ambient current treatments (T1-T6), wave energy during wave passage caused only minor plant movement patterns (Figure 12 a-d). The only consistent movement pattern was a slight decrease (i.e., < 10 deg) in the angle of orientation, with a slight vertical spreading of apical tips as waves approached, continuing until wave crest passage. Plant shoots were reoriented by the ambient current and oribital wave currents after wave crest passage.

For the intermediate current treatments (T7-T12), plant movement patterns illustrated in Figure 13 (a-d) indicate that ambient current forces were not able to counteract the orbital forces in the passing waves. One of the seemingly most significant differences in plant movement under these treatments occurred as the wave trough passed over shoot material floating on the water surface. During passage of this portion of the wave cycle, floating shoot material was pulled by the countercurrent toward the next approaching wave crest. This “upstream” movement of floating shoot material reoriented the underwater shoot section to near vertical (i.e., approaching a 90-deg angle of orientation). As the wave crest passed, orbital currents on the backside of the wave pulled the shoot material with the wave and reestablished the original orientation. The main effects of this movement pattern were entanglements, which occurred as the shoot was pulled upstream during wave approach, and peak tensile loading, which occurred as the shoot material was returned to its original orientation during wave passage.

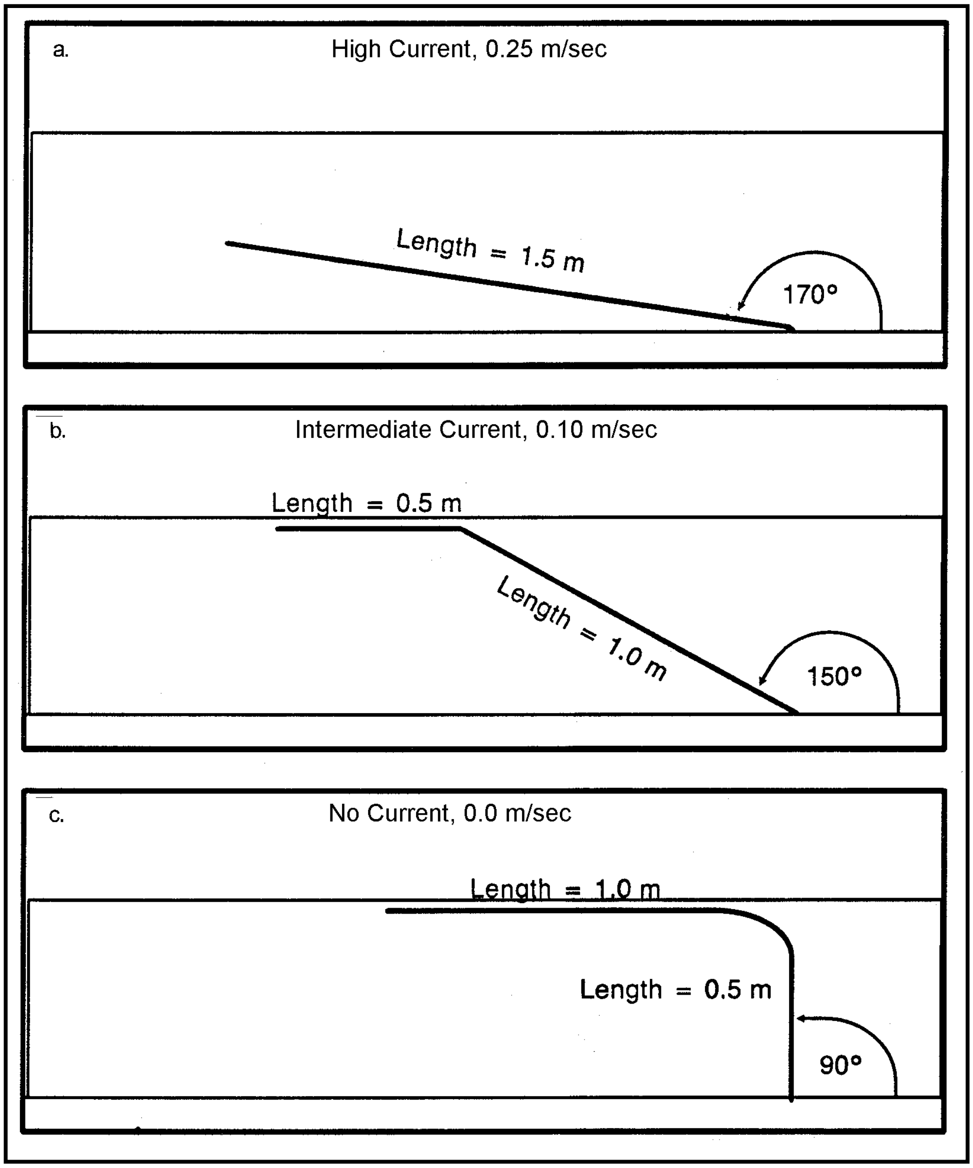

Figure 11. Ilustration of the effects of the three current settings on the orientation of an 8-week-old Eurasian watermilfoil shoot within the flume

Plant movement patterns during wave passage under ambient conditions of no current are illustrated in Figure 14 (a-d). Under these conditions, shoot material was again pulled toward the approaching wave crest by countercurrents in the wave troughs. This movement, in the absence of ambient current, resulted in a reduction in the angle of orientation of the main shoot axis to approximately 65 deg. As with the intermediate ambient current treatments described above,

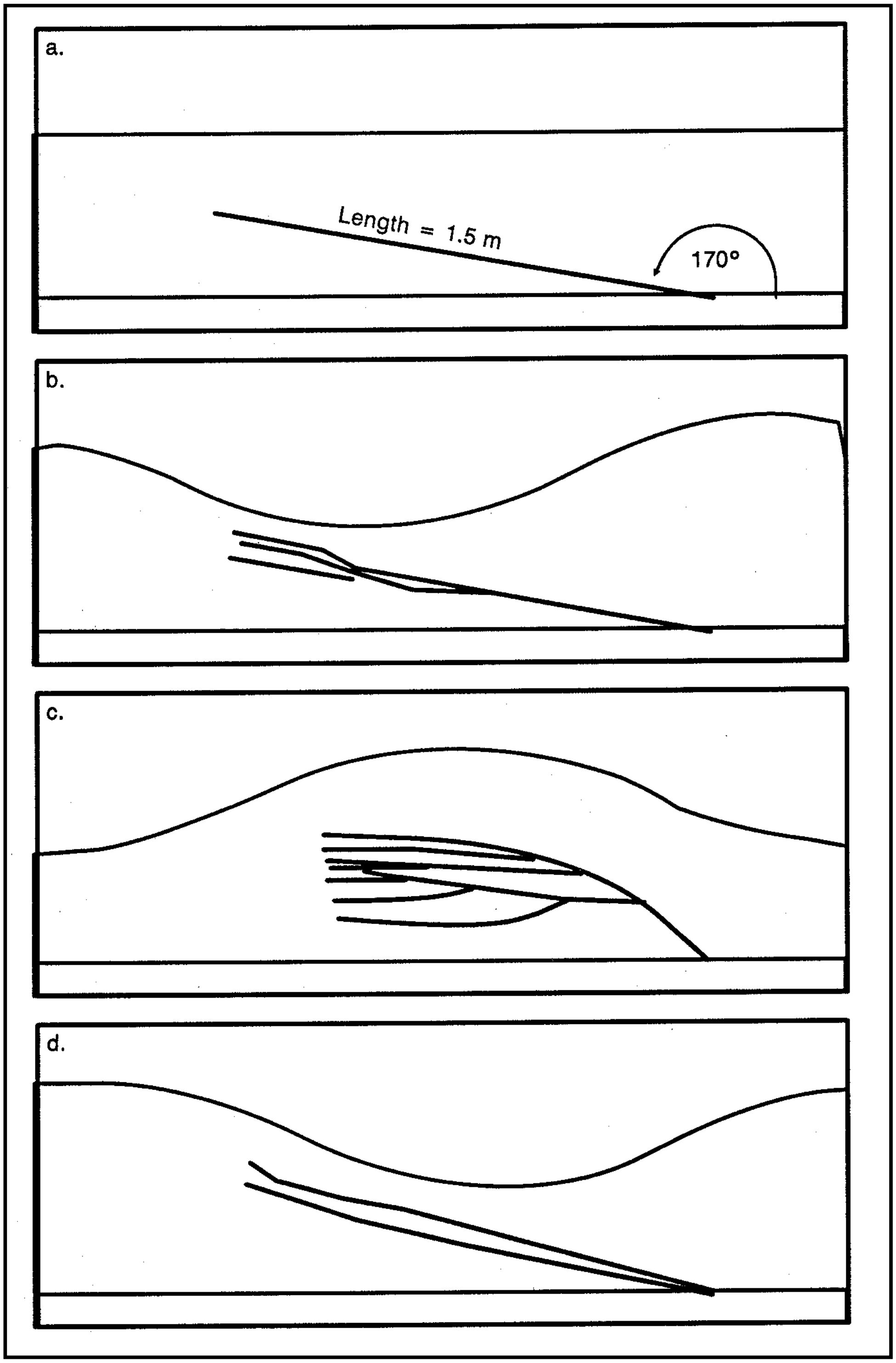

Figure 12. Illustration of generalized movement patterns of 8-week-old Eurasian watermilfoil shoots during passage of a 0.3-m wave under the high current velocity (0.25 m/sec) treatment

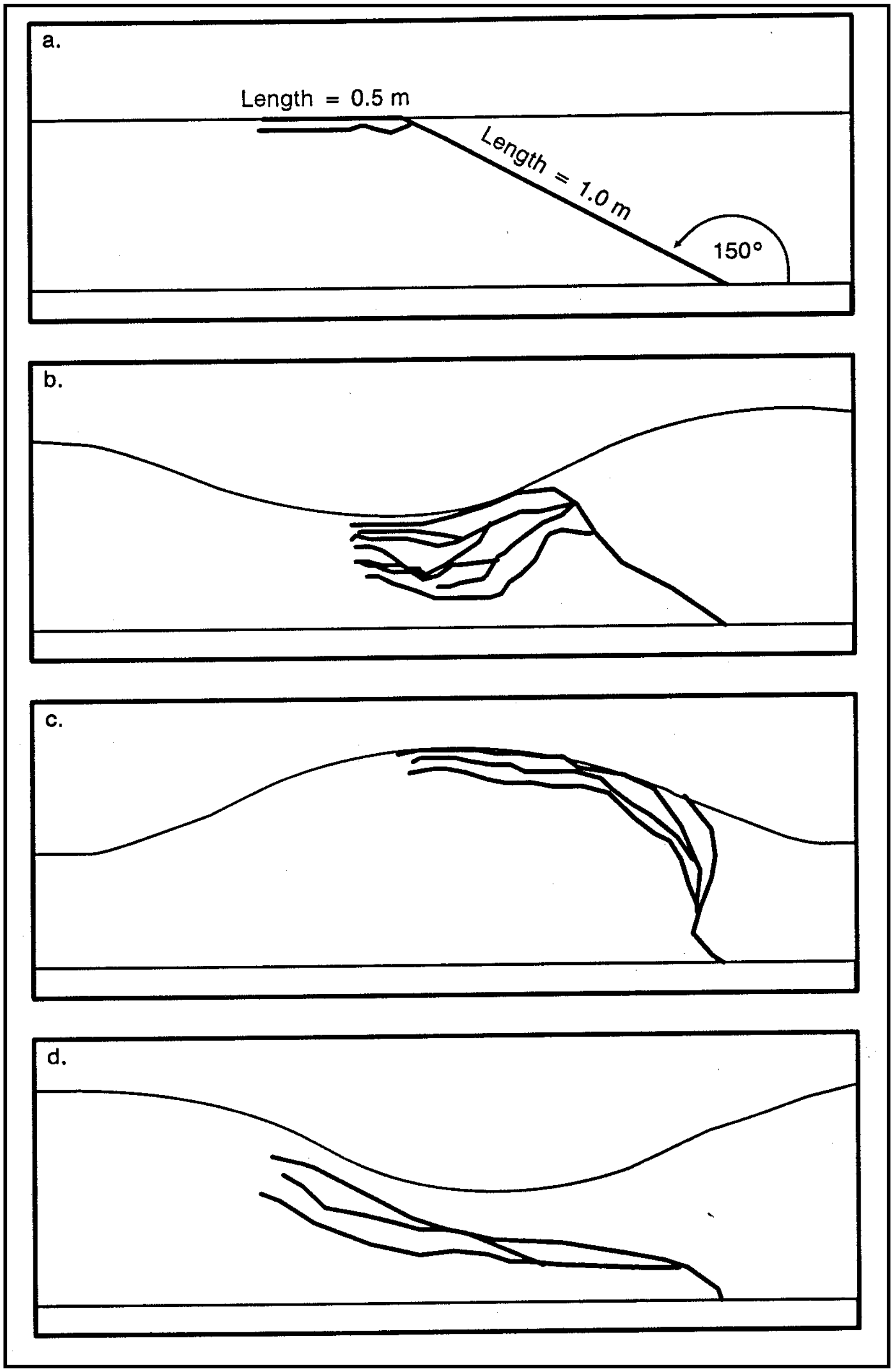

Figure 13. Illustration of generalized movement patterns of 8-week-old Eurasian watermilfoil shoots during passage of a 0.3-m wave under the intermediate current velocity (0.10 m/sec) treatment

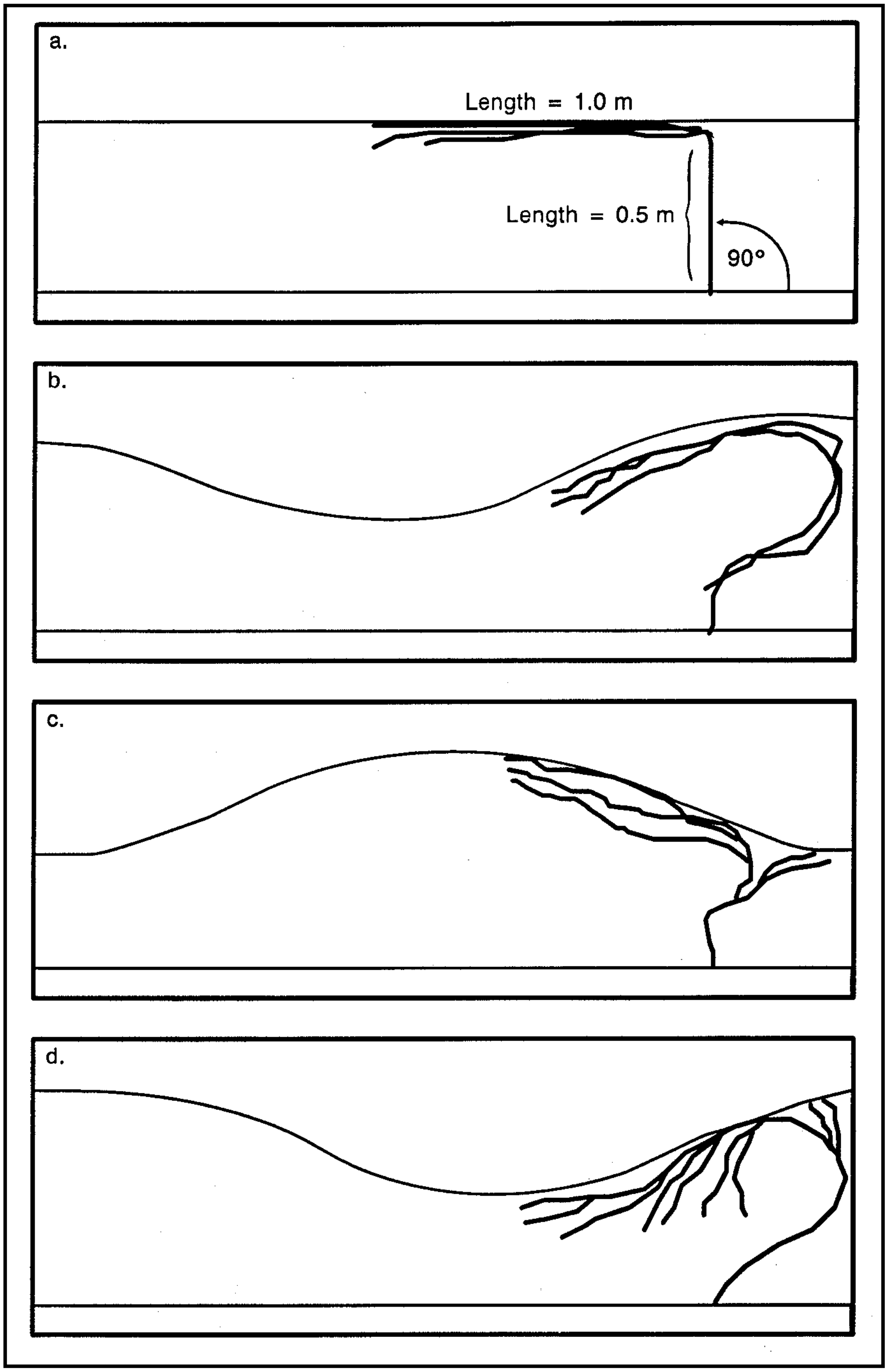

Figure 14. Illustration of generalized movement patterns of 8-week-old Eurasian watermilfoil shoots during passage of a 0.3-m wave under treatments with no ambient current

this also lead to considerable entanglement of shoot material floating on the water surface. During wave passage, orbital currents on the backside of the wave reoriented shoot material at the water surface and changed the angle of orientation of the main shoot axis to approximately 115 deg. Because the majority of the shoot mass was either floating or near the water surface and consequently exposed to the main wave orbit, considerable entanglement occurred during wave passage. It appears that this entanglement led to the increased loss of shoot mass from these treatments.

Species and age effects

The observations described above were made for 8-week-old milfoil plants under the different ambient current velocity treatments. In comparison to the observations described above for 8-week-old milfoil plants, 8-week-old vallisneria plants exhibited the same general movement patterns. However, due to the smooth texture of vallisneria leaves and to the lack of branches on individual leaves, vallisneria plants did not exhibit the same tendency to become entangled as did milfoil shoots. Consequently, very little damage occurred from breakage due to entanglement except, perhaps, to flowers. Vallisneria flower pedicels, which become coiled after seed fertilization to effect the resubmergence of the seed pod, did show a tendency for entanglement and subsequent breakage, especially under the intermediate current velocity treatments.

Regarding the effects of plant age on wave exposure and damage, the major difference was the reduced amount of entanglement in 4-week-old plants. For 4-week-old milfoil plants, which had less mass near the water surface under intermediate and no-current treatments, shoots became entangled to a lesser degree than in 8-week-old plants. Also, 4-week-old milfoil plants had fewer flower spikes, which were observed to be more brittle than vegetative shoot sections and which significantly contributed to 8-week-old fragment collections (Figure 8). For vallisneria, 4-week-old plants had significantly less mass than 8-week-old plants, and due to reductions in leaf length, leaf tips were held below the water surface during treatments with positive ambient currents. Consequently, 4-week-old plants had fewer leaf tips exposed to waves than 8-week-old plants. Further, 4-week-old vallisneria plants did not have any flower pedicels from which to generate fragments.

Wave Height Effects on Tensile Loading

Estimates of tensile loading on 8-week-old milfoil shoots under the hydrological conditions used in Treatments 10, 11, and 12 are shown in Figure 15. Under these current velocity and wave period conditions (T10-T12, Table 2), wave heights of 0.1 m generated a peak tensile load in the range of 25-50 g (Figure 15a). At wave heights of 0.2 m, peak tensile loads ranging from 75 to 100 g were recorded (Figure 15b). Exposure to wave heights of 0.3 m generated peak tensile loads predominately between 100 and 150 g (Figure 15c).

Obviously, increases in wave height resulted in greater tensile loading generated on the basal portion of the milfoil shoot. Also illustrated in Figure 15 is the fact that the peak load was only generated for a small portion of time during wave passage. In Figure 15, the plant's movement pattern in response to exposures to repeating 5-sec waves (i.e., wave period) is apparent. Peak loading occurred for a short duration and indicates that portion of time during wave passage that the plant shoot was fully extended in the direction of the passing wave (Figure 13d). The reductions in loading between loading peaks indicated in Figure 15 are the result of the plant being recoiled by the counterclockwise current in the wave troughs between wave crests (Figure 13b).

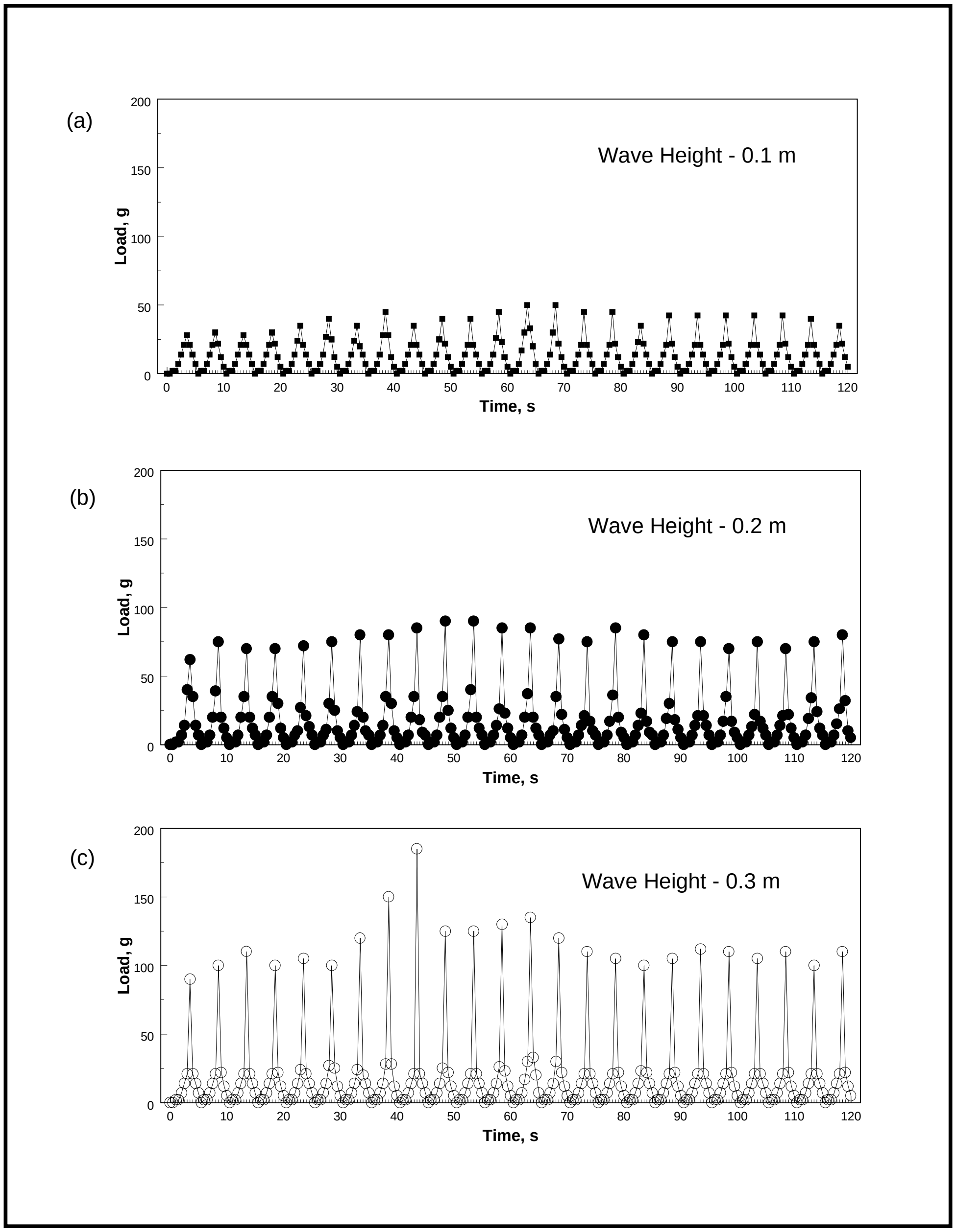

Figure 15. Tensile loading measured on an 8-week-old Eurasian watermilfoil shoot during exposure to a repeating series (W_p = 3 sec) of waves with heights of (a) 0.1 m, (b) 0.2 m, and (c) 0.3m. (Ambient current velocity = 0.10 m/sec). Tensile load measured at base of the sheet)

Mechanical Properties of Field Plants

Collections of plant specimens for seven species were made from Lake Onalaska, WI, during August 1995 to provide measurements of the mechanical properties of UMR field-propagated plants. Breaking forces of the basal (Zone 1) and apical (Zone 3) sections of dominant shoots of these field-collected plants are compared with similar measurements of greenhouse-cultured milfoil plants used in this study in Figure 16. As shown in Figure 16a, Zone 1 breaking forces were higher in six of the seven field-collected plant species, with only *Ceratophyllum demersum* showing breaking forces as low as 4-week and 8-week milfoil cultures used in this study. Zone 3 breaking forces for five of the seven field-collected species were higher than milfoil plants used in this study (Figure 16b). Also, field-collected milfoil specimens had a Zone 3 breaking force of approximately twice that of greenhouse-cultured plants.

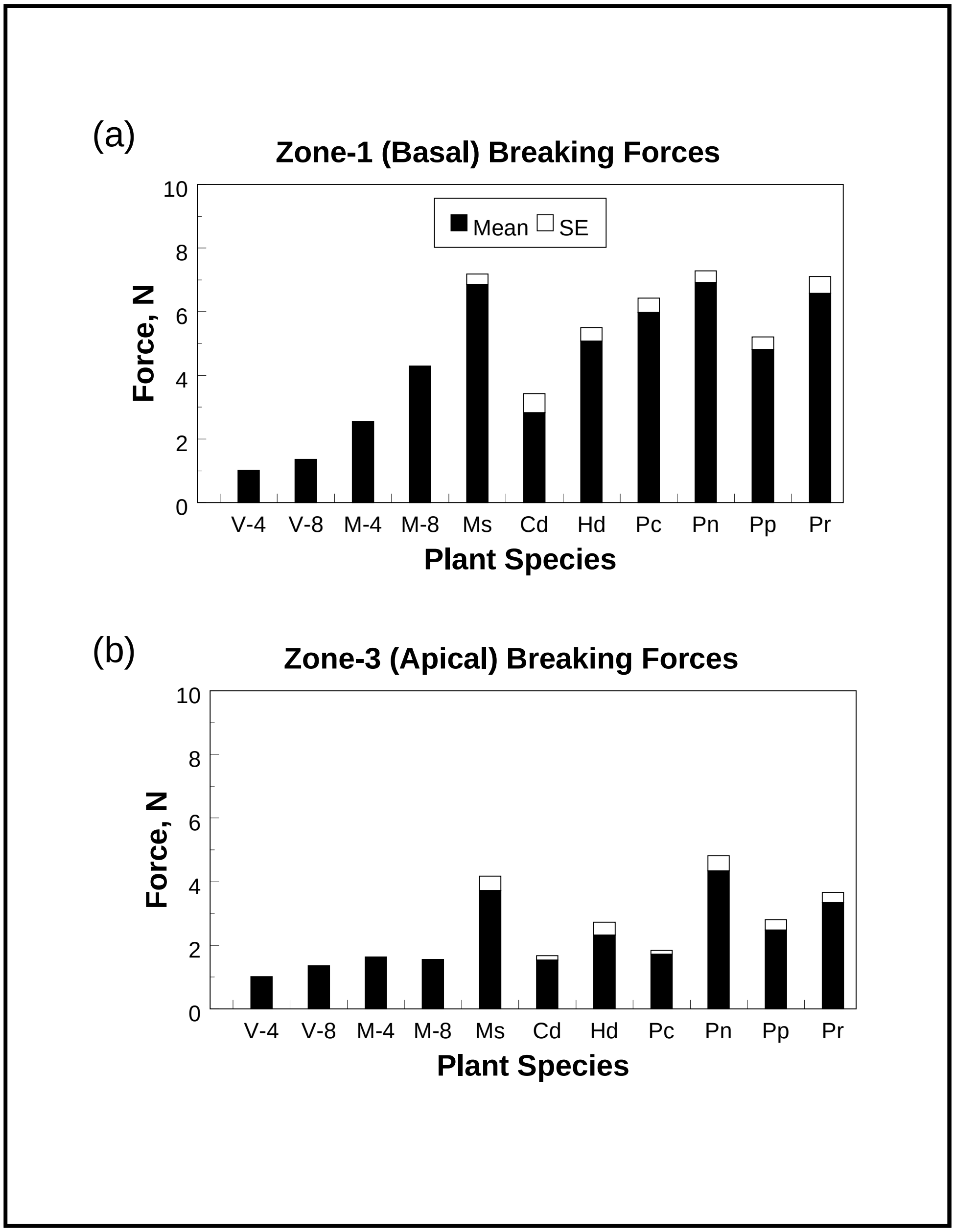

Figure 16. Breaking forces of plant shoots collected from Lake Onalaska, WI, August 1996. (Species are: Ms – Eurasian watermilfoil, Cd – coontail, Hd = water stargrass, Pc – curly-leaf pondweed, Pn – American pondweed). For comparison breaking forces are also shown for both 4- and 8-week-old greenhouse-cultured plants used in this study)