flowers in this study are not clearly identified. Tissue hydration may be significant, based on considerably lower-than-expected water content. The stigma–style component had a mean fresh weight of 6.8% or 13.9 mg H_2O per stigma–style. Ovaries averaged 13.8% H_2O or 31 mg H_2O per ovary. These levels of tissue hydration are considerably less than that assumed to exist in citrus flowers, often referred to as succulent tissues highly intolerant of freezes. However, citrus leaf callus supercools to −11°C, regardless of 94% to 97% H_2O content (unreported data).

The significant delay in freezing of detached citrus parts agrees with results of deciduous fruit trees (11) and is notable in at least two situations. One is the use of detached citrus leaves to determine lethal freezing points (1), and the second is in determining the role of xylem discontinuity in freeze survival (7). Apparently, correction factors are appropriate for determining critical freeze temperatures based on DTA of detached plant parts, and liquid phase discontinuity in the xylem may be as important in freeze tolerance of subtropical citrus trees as that inferred in temperature deciduous species (7). The factor of water column tension has not been addressed in citrus freeze trials, and the effect of detachment on tissue hydration is unknown. In peach trees, there appears to be a constitutive part of mature wood that limits supercooling to about −2°C (3).

The supercooling levels found in this study are adequate to accommodate the probability of freeze severity (6) that coincides with citrus bloom in central Florida, a major citrus area. However, the role of supercooling in citriculture is yet unclarified under natural freezes, and controlled supercooling is a formidable research challenge (4).

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Seedling Emergence Forces of Vegetable Crops

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Abstract. Individual seedling emergence forces were determined for nine vegetable crops with an universal testing instrument (Model TTCM Instron). The seed energy content also was calculated with an oxygen bomb calorimeter. Seed weights of the different crops were correlated with seedling forces and the seed energy content. The time required to achieve the maximum force varied among crops and the pressure exerted varied from 26 mN for table beet (*Beta vulgaris* L.) to 3400 mN for snap bean (*Phaseolus vulgaris* L.). Equipment was developed to measure the combined seedling emergence forces of 50 seedlings. Snap bean seeds were sized into three groups: 200, 275, and 350 mg per seed. Total force, percent seedling emergence, force per seedling, pressure exerted, and energy content increased in a linear trend as seed size increased. An inverse relation existed between the capacity of seeds to use reserve materials and seed size. Small-sized seeds were more efficient in using reserve materials than large ones.

Sowing seeds (and their subsequent germination) and seedling establishment are annual events in vegetable crop production. A good plant stand is essential for maximum yield potential and harvest efficiency. To accomplish this goal, the seed must complete germination and then emerge through the soil surface. The soil can act as a physical barrier to seedling emergence and may decrease or even prevent seedling establishment, especially under conditions of soil crusting (7) or soil compaction (17).

The emergence ability (EA) of a seedling can be described by the following formula: EA = EF·Ch·Sp (8). In this equation, EF is the vertical elongation force or emergence force. Ch is the morphological characteristic of the seedling. Sp is the speed of elongation or the time to achieve maximum force. The morphological character is the shape, or, more specifically, the cross-sectional area of the emerging seedling. From this discussion, a monocot should have a greater emergence ability than a dicot, since the former has a smaller surface area to penetrate the soil surface than the latter.

Several methods have been described to quantify seedling emergence forces (15); however, the use of a force transducer interfaced with a chart recorder may be the best method (8). Goyal et al. (5) summarized seedling emergence forces recorded from 1950 to 1977. Recent work on emergence forces have been reported for leguminous crops (8), cotton (2), and soybean (13).

The purpose of this study was to quantify seedling emergence forces for several different vegetable crop seedlings. A method is

Table 1. Individual seedling emergence force characteristics of vegetable crops.

Crop	Seed wt (mg)	Maximum force (mN)	Time to achieve maximum force (hr)	Pressure exerted (kPa)	Energy content (J)	Use of reserves (N·kJ⁻¹)
Snap bean	268.0	3400 ± 360	21 ± 1	234	4554 ± 12	0.75
Radish	10.0	558 ± 88	19 ± 8	317	231 ± 1	2.40
Cucumber	31.4	241 ± 49	9 ± 3	63	801 ± 1	0.30
Cabbage	4.20	157 ± 24	11 ± 2	241	111 ± 1	1.41
Onion	4.04	83 ± 11	19 ± 4	259	90.4 ± 0.2	0.92
Tomato	2.90	44 ± 5	10 ± 2	96	71.8 ± 0.1	0.61
Carrot	1.00	35 ± 9	5 ± 1	117	23.8 ± 0.1	1.47
Lettuce	1.07	29 ± 6	7 ± 2	89	27.3 ± 0.1	1.06
Beets	---	26 ± 6	4 ± 2	62	---	---

[z]Mean ± SE.

Table 2. Seedling emergence force characteristics from sized snap bean seeds. Fifty seeds were sown in sand and the emergence forces were measured as the hypocotyls emerged through the sand surface.

Relative seed size	Seed wt (mg)	Total force (N)	Time to achieve maximum force (hr)	Seedling emergence (%)	Force per seedling (N)	Pressure exerted (kPa)	Energy content (kJ)	Use of reserves (N·kJ⁻¹)
Small	200	123	32	79	3.12	225	3.38	0.92
Medium	275	160	34	88	3.61	249	4.67	0.77
Large	350	192	43	89	4.30	270	5.98	0.72
Linear significance		**	NS	**	**	**	**	*

[ns,*,**]Nonsignificant or significant at the 5% or 1% levels, respectively.

described to determine the combined emergence force of a representative sample of seedlings, and the influence of seed size on emergence forces was studied in snap beans.

The emergence forces of nine vegetable crops were quantified, including 'Bush Blue Lake 47' snap bean, radish (*Raphanus sativus* L. 'Champion'), cucumber (*Cucumis sativus* L. 'Calypso'), cabbage (*Brassica oleracea*, Group *capitata* 'King Cole'), onion (*Allium cepa* L. 'Southport White Globe'), tomato (*Lycopersicon esculentum* Mill 'New Yorker'), carrot (*Daucus carota* L. 'Scarlet Nantes'), lettuce (*Lactuca sativa* L. 'Montello'), and 'Ruby Queen' table beets. All samples were obtained from commercial seed lots maintained at 5°C and 30% RH. All seeds had epigeal germination.

A universal testing instrument model TTCM Instron (Instron Engineering Corp., Canton, Mass.) was used to record emergence forces generated from individual seedlings. Seeds were sown in a 0.6-liter container filled with pasteurized builder's sand. The sand was watered to 15% moisture content, covered, and incubated at 25°C in darkness. One seedling was positioned on the universal testing instrument when the hypocotyl was visible at the sand surface. A plastic cap was fitted over the emerging hypocotyl and was connected to the load cell of the Instron (16).

The emergence force was recorded until the maximum force was generated. The study was conducted at room temperature (≈25°C) and light was excluded from the seedlings, since light induces hypocotyl hook opening (10). Data collected from the chart recorder included the maximum force in newtons (N) and the time in hours to reach the maximum force. The diameter of the hypocotyls was measured to calculate the force per unit area expressed as kilopascals (kPa). A minimum of five replications of force tests was performed per crop. The energy content of seeds was determined with an oxygen bomb cal-

orimeter, model 1241 (Parr Instrument Co., Moline Ill.). Data originally expressed as calories were converted to joules (J) per seed. The use of reserve materials by seeds was calculated as the maximum force generated per available stored energy (N·kJ⁻¹).

Equipment was developed to measure the combined seedling emergence forces of a representative sample of seedlings. Thus, the performance of a seedlot could be estimated more effectively than by drawing inferences from an individual seedling. A 25 × 17.5 × 1.2 m × 10⁻² plexiglass plate was attached to a 200-N load cell (Eaton Corp., Troy, Mich.). A strain gage conditioner Model 3270 (Daytronic Corp., Miamisburg, Ohio) interfaced the load cell with a chart recorder (Measurement Technology, Denver, Colo.).

'Bush Blue Lake 47' snap bean seeds, from the same seedlot, were sized into three groups; 200, 275 and 350 mg per seed. Fifty seeds of each size were sown in plastic containers filled with pasteurized sand and watered to 15% moisture content. The container with seeds was maintained at 25°C until the hypocotyls were visible at the sand surface. The emerging seedlings were then positioned under the plexiglass plate, and the emergence forces were monitored over time. The total force, time to reach maximum force, and percent seedling emergence were determined. The seed energy content, pressure exerted, and the seed's capacity to use reserve materials were calculated as previously described. There were four replications per treatment and the treatment sums of squares were partitioned into single degrees of freedom.

A wide range of forces and times to attain maximum force were measured among species (Table 1). In general, seedling emergence forces were greatest for large-seeded crops. A significant correlation ($r = 0.98$**) was found between seed weight and emergence forces for the crops shown in Table 1.

Table beets were excluded from this correlation, since the seed structure is not a true seed.

We found an emergence force for radish of 558 mN (Table 1), which compares favorably with 0.42 N previously reported (3). However, cucumber exerted an emergence force of 241 mN (Table 1), in contrast to 1.57 N reported previously. Differences may be attributed to methodology employed and cultivars studied. Other crop comparisons are not possible due to the lack of information in the literature on vegetable crop emergence forces.

The force per cross-sectional area of hypocotyl varied among species. Radish exerted the greatest pressure of 317 kPa and onion, the only monocot studied, produced a relatively high pressure, which was attributed to the small cotyledon diameter. The pressure exerted was not correlated ($r = 0.21$) with seed weight.

The seed energy content varied among crops and was correlated with seed weight ($r = 0.99$**). The energy content is dependent on the composition and amount of stored materials within the seed, and ranged from 17.0 to 26.3 J·mg⁻¹ of seed. The cruciferous crops and carrots had a greater capacity to use reserve materials and generate force. In general, small-seeded crops exerted greater force per stored energy than large-seeded crops.

The pattern of seedling emergence forces developed from 50 sown snap bean seeds is illustrated in Fig. 1. A sigmoidal-shaped curve is observed until maximum seedling forces are attained after 36 hr. The maximum force is maintained for a period of several hours, followed by a gradual decline. A longer period of time is required to attain maximum force for a group of seedlings (Fig. 1, Table 2) compared to a single seedling (Table 1).

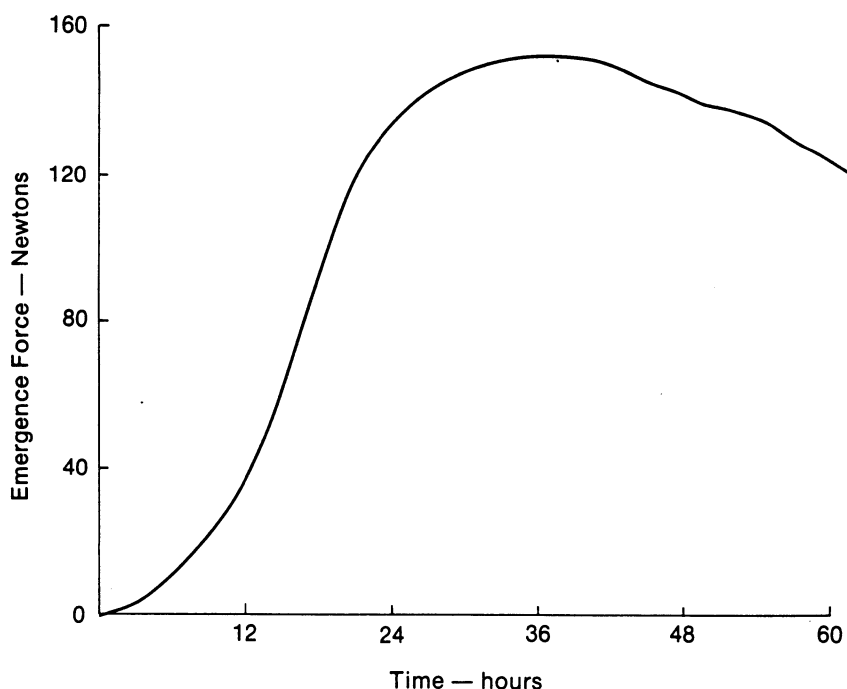Total force, percentage seedling emergence, force per seedling, and seedling pres-

Fig. 1. The pattern of seedling force development in snap bean seedlings. Fifty seeds were sown in sand and the emergence forces were measured as the hypocotyls emerged through the sand surface. (Redrawn from chart recordings.)

sure increased in a linear trend as seed size increased (Table 2). In our study, a trend existed (although not significant) that small-seeded snap beans reach maximum force faster than large seeds. A significant positive correlation has been reported between emergence force and seed size among different forage legume species (9, 18, 19). Similar correlations have been reported among cultivars of forage legumes (19) and large-seeded legumes (8). Small-seeded soybean cultivars required less time to exert maximum force than large-seeded cultivars (13).

The bean seed energy content increased with seed size and was ≈17.0 J·mg^{-1} of seed. An inverse relation existed between the seeds capacity to use reserve materials and seed size. Thus, it appears that small-sized seed are more efficient in using reserve materials than large ones.

The measurement of seedling emergence forces resulted in a physical barrier to hypocotyl elongation, which induced hypocotyl swelling. A 36% increase in hypocotyl cross-sectional area occurred in snap beans after physical impedance (data not shown). Physical impedance of seedling emergence has resulted in hypocotyl swelling in soybean (11, 14), tomato (12), and calabrese (6). Ethylene has been shown to increase dramatically after seedling elongation was arrested by a physical barrier (4, 14). Ethylene causes hypocotyl thickening by decreasing cell elongation and increasing radial expansion. The practical significance of hypocotyl thickening can be observed in relation to seedling emergence through a crusted or compacted soil. As the diameter of a hypocotyl increases, it can support a greater compression load and resist bending and breaking (12). Thus, an increase in diameter would enable the seedling to exert greater total force (4).

This report provides data on seedling emergence forces and seed energy content of several vegetable crops. Equipment and procedures are described that quantify the combined seedling emergence forces from a representative sample. Seed weight was positively correlated with seedling emergence forces and seed energy content. Emergence forces should be considered relative rather than absolute, since several factors may influence these measurements.

The inherent seed quality or seed vigor has been shown to be related to emergence capacity (1). Environmental factors including water and temperature stress can influence seedling emergence forces (2, 19). The method employed to quantify emergence forces can affect the measurements (15). A force transducer appears well-suited to measure these forces (8); however, considerable time is required to obtain information.

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