Soaking Temperature of Dried Tuberos Roots Influences Hydration Kinetics and Growth of *Ranunculus asiaticus* (L.)

Christopher B. Cerveny^{1,2} and William B. Miller

Department of Horticulture, Cornell University, Ithaca, NY 14853

Thomas Björkman

Department of Horticulture, Cornell University, Geneva, NY 14456

Neil S. Mattson

Department of Horticulture, Cornell University, Ithaca, NY 14853

Additional index words. Persian buttercup, hydration injury

Abstract. The published literature is inconsistent with recommendations for hydrating *Ranunculus asiaticus* (L.) dried tuberos roots, a common practice in commercial production systems for this ornamental geophyte. Imbibition rate increased with hydration temperature but to lower equilibrium moisture content than when hydrated at cooler temperatures. In the greenhouse, survival was predicted to be greatest when tubers were hydrated at 20 °C. Plant height, visual quality, and foliar dry weight followed a similar trend 4 weeks after planting. These results demonstrate that a hydration temperature between 15 and 25 °C is required to obtain good quality when growing *R. asiaticus* from its dried tuberos roots.

Ranunculus asiaticus is a traditional cut flower and flowering potted plant that has become popular in early spring gardening and landscape designs (Hamrick, 2003). *R. asiaticus* is often grown from seed or from its dried tuberos roots (hereafter abbreviated “roots”), which flower faster and more profusely than from seed (Meynet, 1993). The roots of *R. asiaticus* are well adapted to lengthy dry storage and have therefore been identified as “resurrection geophytes” (Beruto et al., 2009; Kamenetsky et al., 2005). It is common commercial practice to hydrate the dry roots before planting, because this provides handling uniformity and facilitates fungicide application (Y. Liberman, personal communication); however, the published information on hydration duration and temperature

is inconsistent. Meynet (1993) suggested direct planting without a hydration treatment, whereas others recommended soaking the roots in slowly running water for 24 h before planting (De Hertogh, 1996; Umiel and Hagiladi, 1999); specific hydration temperature recommendations were not provided. While investigating the effect of stratification on *R. asiaticus* flowering, Ohkawa (1986) submerged the roots 8 h at 6 °C before planting. It is important to establish a unified *R. asiaticus* root hydration protocol for future scientific work and for consistent commercial production.

Because several processes could limit the rate of hydration in *R. asiaticus* roots, an appropriate hydration kinetics model must be selected. An empirical model for describing moisture sorption curves, the Peleg model, has been used to model water uptake in a number of dehydrated and rehydrated products including seeds of kidney bean (*Phaseolus vulgaris* L.), chick pea (*Cicer arietinum* L.), and field pea (*Pisum sativum* L.) along with rice (*Oryza sativa* L.) and other cereal grains and other food products (Abu-Ghannam and McKenna, 1997; Bello et al., 2008; Hung et al., 1993; Peleg, 1988; Prasad et al., 2010; Sarchetti et al., 2003; Sopade et al., 1992; Turhan et al., 2002). The advantage of using Peleg’s model for estimating moisture uptake is the ability to predict long-range moisture gains from relatively short duration experiments (Peleg, 1988).

In this research, the Peleg model was investigated for applicability in modeling *R. asiaticus* hydration. Subsequent greenhouse experiments demonstrate the influence of hydration temperature on plant growth.

Hydration kinetics. Dried roots of *Ranunculus asiaticus* ‘Tecolote Pink’ were obtained from a commercial producer (see specific experiment) and randomly assigned to one of three distilled water temperature regimes: 5, 20, or 35 °C. There were five replications per treatment with five sub-sample roots per replicate. Roots were submerged for 1 h, removed, blotted dry, weighed, and then re-submerged. Data were collected hourly for 12 h and then after at 24 h and 30 h. After 30 h, roots were placed in a 70 °C oven and dried until constant weight was achieved.

Model fitting. Turhan et al. (2002) used the Peleg model to describe moisture sorption in chickpea; much of their work is adapted for interpretation and presentation of our results. The two-parameter sorption equation proposed by Peleg (1988) is considered for modeling *R. asiaticus* hydration:

$$M(t) = M_0 \pm \frac{t}{K_1 + K_2 t} \quad [1]$$

where $M(t)$ is the dry basis moisture content of roots at time t (%), M_0 is the initial moisture content (%), K_1 is the Peleg rate constant (h/%), and K_2 is the Peleg capacity constant (%). Because we are modeling an adsorption/absorption process, the “±” in Eq. [1] becomes positive (+).

The first derivative of the Peleg equation, Eq. [2], gives the momentary sorption rate (S).

$$S = \frac{dM(t)}{dt} = + \frac{K_1}{(K_1 + K_2 t)^2} \quad [2]$$

The Peleg rate constant, K_1 , inversely relates to the initial sorption rate (i.e., S at time zero, or $t = t_0$).

$$S_0 = \frac{1}{K_1} \quad [3]$$

The Peleg capacity constant, K_2 , relates to the equilibrium moisture content, M_E , as time approaches infinity.

$$M_E = M_0 + \frac{1}{K_2} \quad [4]$$

The model was fit to our data using Eq. [1] and non-linear model fitting procedures in JMP (SAS Institute, Cary, NC) to generate values for K_1 and K_2 . M_0 was calculated directly from our data. To verify the accuracy of the Peleg model for predicting water uptake in *R. asiaticus*, Eq. [1] was rearranged to its linear form, Eq. [5], with linear regression used to provide a coefficient of variance (R^2).

$$\frac{t}{M(t) - M_0} = K_1 + K_2 t \quad [5]$$

The hydration ratio, R , at a given value of $M(t)$ may be calculated by Eq. [6].

$$R_t = \frac{M(t) - M_0}{M_E - M_0} \quad [6]$$

Once a value for a desired hydration ratio is determined, R_{t1} , it may be subsequently used to estimate the time necessary to achieve other hydration ratios, R_{t2} .

Received for publication 6 Sept. 2011. Accepted for publication 19 Nov. 2011.

This work constitutes a portion of a dissertation submitted by C.B. Cerveny to the Graduate Faculty of Cornell University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

We thank the Fred C. Gloeckner and Post-Schenkel Foundations for grant support, The California Flower Bulb Co. and The Flower Fields at Carlsbad Ranch for donation of plant materials, and the Cornell Statistical Consulting Unit for assistance with data analysis. We also thank Joanna Blaszcak, Suzana Markolovic, and Siddharth Ramshankar for their assistance with data collection.

¹Current address: ScottsMiracle-Gro, Research and Development, 14111 Scottslawn Road, Marysville, OH 43041.

²To whom reprint requests should be addressed; e-mail Chris.Cerveny@Scotts.com.

$$\frac{R_{t1} \cdot (1 - R_{t1})^{-1}}{t_{R1}} = \frac{R_{t2} \cdot (1 - R_{t2})^{-1}}{t_{R2}} \quad [7]$$

Greenhouse Expt. 1. Dried roots of *Ranunculus asiaticus* ‘Tecolote Pink’ from the 2006–2007 growing season were obtained in Sept. 2008 from a commercial source (California Flowerbulb Co., Carlsbad, CA) and were stored at 15 °C and ≈50% relative humidity as per common commercial practice until treatments were initiated on 6 Oct. 2008. Tissue was submerged in tap water at 5, 17, 23, or 35 °C for 24 h and then given a 5-min soak in a copper sulfate biocide (Phyton-27; Phyton Corp., New Hope, MN)

Fig. 1. Hydration kinetics of *R. asiaticus* roots submerged in distilled water. Data are means ± SE.

Fig. 2. Linearization of moisture sorption curves of *R. asiaticus* roots submerged in distilled water. $M(t)$ and M_0 are the moisture contents (% dry basis) at Times t and 0, respectively. Data are means ± SE.

Table 1. Water sorption parameters calculated (calc.) or observed (obs.) from *R. asiaticus* roots hydrated in distilled water.

Temperature (°C)	Initial Moisture (%)	Moisture content ^a (%)			Calc. M_E^y (%)
		After (h)	Calc. ^z	Obs.	
5	23.0	12	149.4	153.3	267.5
		24	189.3	195.4	
20	22.4	12	176.3	177.8	249.5
		24	205.7	208.6	
35	23.2	12	185.1	188.6	230.3
		24	204.7	205.0	

^aSee Eq. [1].

^ySee Eq. [4]. M_E is the equilibrium moisture content.

^zCalculated on a dry weight basis.

at 1375 mg·L⁻¹ metallic copper. A series of incubators were used to achieve constant temperature during the hydration period. Roots were planted four per pot on 7 Oct. in 15-cm diameter azalea pots using a commercial potting mix (Sun Gro LC1; Sun Gro Horticulture Canada Ltd., Vancouver, British Columbia, Canada) with crowns covered by ≈2 cm of substrate. Planted roots were moistened with tap water and then held at 5 °C for 4 weeks to allow some root establishment before growing in a 15 °C set point temperature greenhouse starting on 4 Nov. The plants were organized in a completely randomized design with six replicate pots of four sub-samples (pooled) per treatment.

Plants were evaluated after 4 weeks in the greenhouse for percent survival (any visible growth), plant height (substrate line to tallest leaf), and shoot dry weight (severed at soil level and dried 3 d at 70 °C).

Greenhouse Expt. 2. Dried ‘Tecolote Pink’ roots were handled in a similar manner as Expt. 1, except the 24-h hydration temperatures were 5, 10, 17, 20, 25, 30, or 35 °C. Treatments were initiated on 8 Dec., and roots were planted on 10 Dec., held for 5 weeks (as described previously), and then moved to the greenhouse on 14 Jan. 2009. Plants were arranged in a completely randomized design with nine replicate pots of four sub-samples (pooled) per treatment. Percent survival and plant height were evaluated after 4 weeks in the greenhouse. After 11 weeks, plants were evaluated for number

of flowering stems (stems with at least one flower) and shoot dry weight (as in Expt. 1).

Greenhouse Expt. 3. The cultivars and tissue sources were increased in Expt. 3. *R. asiaticus* ‘Tecolote Pink’ and ‘Labelle Cream’ were obtained from 2007–2008 growing seasons in southern California (same source as described previously) and France (unknown origin), respectively. Additionally ‘Tecolote Red’ and ‘Tecolote White’ from the 2008–2009 growing season were also obtained from southern California. Roots were held at 15 °C and ≈50% relative humidity until treatments were initiated on 28 Sept. 2009. Roots were hydrated at 5, 15, 25, or 35 °C for 24 h, treated with a copper biocide, and planted as described previously. After 6 weeks cooling at 5 °C, plants were moved to the greenhouse on 9 Nov. Percent survival, plant size (mean of height and two cross canopy diameter measurements), and shoot dry weight (as described previously) were calculated after 4 weeks in the greenhouse (7 Dec. 2009). A visual plant quality ranking was also assigned on a 1–5 scale: 1 = poor quality, one to two leaves, diseased and/or dying; 2 = unacceptable quality, slightly more growth, three to six leaves; 3 = acceptable quality, seven to 10 leaves, non-uniform growth; 4 = moderate quality, uniform growth, greater than 10 leaves; 5 = best quality, ideal size and shape, greater than 10 leaves.

For greenhouse Expts. 1–3, all measurements and subsequent analyses were conducted on plants showing visible growth. All data were analyzed using standard least squares in JMP (SAS Institute, Cary, NC) with specific models as indicated for each experiment.

Results and Discussion

Assessment of the model. *Ranunculus asiaticus* exhibited typical absorption behavior at all temperatures tested, initially absorbing water rapidly and slowing as moisture content approached equilibrium (Fig. 1). The hydration rate was faster at warmer temperatures but to a lower equilibrium than when hydrated cooler. To assess the model fit, the linear form of the Peleg model [Eq. (5)] is shown in Figure 2 with coefficient of variance (R^2) values from 0.96 to 0.99. It should be noted that Eq. [5] was only used to obtain R^2 terms (Fig. 2); thus, values for K_1 and K_2 used for further analyses were generated by our statistical software package using the Peleg model [Eq. (1)] in standard format. When comparing our calculated to observed moisture content in hydrating *R. asiaticus* roots, the model’s predicted values were within 3% of our observed values at both 12 and 24 h hydration (Table 1).

The Peleg rate constant, K_1 , is related to the mass flux (rate of weight change) in that a lower value of K_1 indicates a faster initial water absorption rate. In our experiment, as temperature increased, K_1 decreased, corresponding to faster initial water absorption at higher temperatures (Table 1). The influence of temperature on the Peleg rate constant is shown in Figure 3 through the linearized Arrhenius equation with an R^2 of 0.91:

$$\ln K_1 = \ln K_0 - \frac{E_a}{R_g T} \quad [8]$$

where K_0 is a constant, the pre-exponential factor, or prefactor (h/%); E_a is the activation energy (kJ·mol⁻¹); R_g is the universal gas constant (8.314 kJ·mol⁻¹/K); and T is the absolute temperature (K). To determine the activation energy, the slope of the line generated in Figure 3 is multiplied by $-R_g$. The resultant activation energy for *R. asiaticus* hydration is 24.8 kJ·mol⁻¹, comparable to other organic substances modeled using the Peleg equation; the resultant activation energies were 29.4 kJ·mol⁻¹ for apricot kernels, 14.8 or 59.3 kJ·mol⁻¹ for chickpeas above or below 55 °C, respectively, and 39.2 or 60.4 kJ·mol⁻¹ for roasted or raw lupin seeds, respectively (Celen et al., 2008; Solomon, 2007, 2009; Turhan et al., 2002).

The Peleg capacity constant, K_2 , is inversely related to maximum water absorption; therefore, the lower the K_2 , the higher the absorption capacity. As hydration temperature

Fig. 3. Arrhenius plot for the Peleg rate constant, K_1 , during hydration of *R. asiaticus* roots. Symbols represent means $\pm$ SE.

Fig. 4. Influence of temperature on the Peleg capacity constant, K_2 , during hydration of *R. asiaticus* roots. Symbols represent means $\pm$ SE.

increased, K_2 for *R. asiaticus* also increased, which indicates lower equilibrium moisture content at 30 °C than at 5 °C (Fig. 4; Table 1). Similar trends in K_2 values were observed when chickpea and kidney bean (*Phaseolus vulgaris* L.) were soaked at increasing temperatures (Abu-Ghannam and McKenna, 1997; Turhan et al., 2002).

Water uptake was faster in warmer water. Because growth or decay will alter the system before 100% saturation is reached, we used 75% of M_E as the threshold for hydration time measurements. The time to achieve 75% of M_E was 30 h at 5 °C and decreased to 15.0 h at 20 °C and 9.6 h at 35 °C (Table 2). Hydrating roots for 12 h at 5, 20, or 35 °C resulted in moisture contents within 57%, 71%, or 82% of M_E , respectively (Tables 1 and 2). Increasing the soaking time to 24 h increased moisture content another 16%, 13%, or 7% to 73%, 84%, or 89% of M_E when hydrated at 5, 20, or 35 °C, respectively (Table 1). At room temperature, soaking for 24 h before potting was considered sufficient to hydrate the tubers. We did not investigate the influence of soaking duration on subsequent plant performance.

Greenhouse experiments. In all three experiments, an optimum hydration temperature was shown in plant survival (Fig. 5; Tables 3 and 4). Percent survival increased with hydration temperature to a maximum at ≈ 20 °C for Expts. 1 and 2 or 15 °C for Expt. 3. Survival then decreased as hydration temperature increased (Fig. 5; Tables 3 and 4). In the first experiment, plant height and foliar dry weight followed a similar trend, although were less affected by temperature when hydrated at 5 °C than at 35 °C (Fig. 5). In the second experiment, plant height after 4 weeks was optimum when roots were hydrated at ≈ 25 °C. Plant height and number of flowers were unaffected by hydration temperature after 11 weeks growth, averaging 22.2 cm and two per plant, respectively. Foliar dry weight did not indicate an optimum hydration temperature but increased linearly with hydration temperature (Table 3).

When the number of tested cultivars was increased in Expt. 3, the overall non-linear nature for plant survival was unchanged, although ‘Tecolote Red’ had the highest survival, followed by ‘Tecolote White’, ‘Labelle Cream’, and ‘Tecolote Pink’ with the lowest (86%, 81%, 64%, and 34%, respectively) (Table 4). The plant visual quality, size, or foliar dry weights after 4 weeks’ growth indicated an optimum hydration temperature of 15–25 °C. Visual plant quality was similar among cultivars (Table 4). When considering plant size, the optimum root hydration temperature was not influenced by cultivar; however, certain cultivars responded

differently to specific hydration temperatures (Table 5). For example, ‘Tecolote Pink’ plants were at least 50% smaller than the other cultivars when hydrated at 5 °C, yet when hydrated at 25 °C, all cultivars had similar size after 4 weeks’ growth. Because ‘Tecolote Pink’ and ‘Labelle Cream’ roots were at least 1 year older than ‘Tecolote Red’ and ‘Tecolote White’, we are able to make some assumptions for root age and temperature susceptibility. ‘Tecolote Pink’ from 2008 was the most susceptible to temperature influence among the cultivars tested (Tables 4 and 5), whereas young roots, ‘Tecolote Red’ and ‘Tecolote White’ (2009), were less affected by temperature. Taken together this suggests that a proper hydration temperature is particularly important for forcing material stored for a longer period. A similar phenomenon is noted in some seeds whereby older seeds are more susceptible to hydration injury than fresh as a result of weaknesses in membrane integrity attributed to the natural aging process (Priestley, 1986; Tilden and West, 1985).

Results were initially surprising. We expected decreased plant survival at higher temperature as a result of the rapid water uptake, a condition commonly observed in large seeds and legumes (Copeland and McDonald, 2001; Priestley, 1986). This trend was clearly evident at 30 °C and above; however, we did not expect to see reduced survival at the low hydration temperature.

It is possible that moderate temperature water helps break dormancy in *R. asiaticus* roots that is not achieved when hydrated cooler. Meynet (1993) speculated that a water-soluble thermolabile compound may be responsible for root dormancy; however, none has been identified. He suggested storing roots for 2 months at 25 °C, 10 d at 35 °C, or 2 d at 40 °C to break dormancy, with those stored at 2 °C maintaining dormancy for more than 6 months. Our results do not support a thermolabile dormancy compound because we obtained good growth after only 24 h of hydration without other dormancy breaking treatments.

An alternative hypothesis is that cooler temperatures cause physiological damage to the cellular membranes [chilling injury (CI)]. In seeds, cold temperatures slow a membrane phase transition during hydration, thus allowing damaging rates of hydration and/or excessive leakage of vital nutrients for growth (Copeland and McDonald, 2001). Pollock and Toole (1966) thought CI in lima bean (*Phaseolus lunatus* L.) caused physical damage to cellular membranes resulting in their rupture. Christiansen (1968) hypothesized that cold prevents a metabolic response in cotton seed (*Gossypium hirsutum* L.) rather than inducing direct physical damage because damage was additive with increased cold duration. Powell and Matthews (1978) hypothesized that so-called CI is the result of imbibition damage rather than the effects of low temperature. This hypothesis was supported in pea (*Pisum sativum* L.) that had seedcoats cut to allow more rapid imbibition, but reducing the water absorption rate through osmotic inhibitors lessened the degree of injury (Tully et al., 1981).

Table 2. Water sorption parameters calculated from hydration of *R. asiaticus* in distilled water.

Temperature (°C)	Calculated sorption rate (%/h) ^a			t_R (h) ^b			
	Initial	After 12 h	After 24 h	$R_{0.5}$	$R_{0.75}$	$R_{0.85}$	$R_{0.95}$
5	22.3	5.1	2.2	9.4	30.0	57.5	195.0
20	41.0	4.1	1.5	4.6	15.0	28.7	97.4
35	63.0	3.0	0.9	2.6	9.6	16.5	56.1

^aSee Eq. [3].

^bSee Eq. [6], Eq. [7], t_R is the time (h) to reach a given hydration level.

Fig. 5. Expt. 1. Influence of root hydration temperature on percent survival (any visible growth after 4 weeks), plant height (substrate line to tallest leaf), and foliar dry weight (severed at soil line and dried 3d at 70 °C) of *Ranunculus asiaticus*. Data are means $\pm$ SE.

It is therefore possible that the same phenomenon, rapid imbibition, is responsible for decreased survival in *R. asiaticus* at both high and low temperatures. Further investigations are necessary to determine if mixing an osmotic or matric inhibitor such as polyethylene glycol (PEG) into the *R. asiaticus* hydration solution will alleviate symptoms observed at potentially damaging temperatures. Because the PEG solution would reduce the rate of water uptake, it may serve to further determine a mechanism for damage outside of the optimum range for growth. It may also be useful to measure solutes (i.e., sugars or ions) in the hydration solution during imbibition, which could further support membrane damage as the reason for reduced viability.

Priming [exposure to periods of brief hydration and re-drying at temperatures above which CI occurs (25 °C)] of soybean seeds (*Glycine max* L.) reduced the cellular damage when seeds were later soaked in 4 °C water (Tilden and West, 1985). In one preliminary experiment, dry *R. asiaticus* roots had improved sprouting when hydrated 24 h at 25 °C, allowed to re-dry 1 week at 25 °C, and then re-hydrated 24 h at 25 °C compared with those given a single hydration period (24 h at 25 °C) (Cerveny and Miller, unpublished data). It is not known if priming *R. asiaticus* roots at moderate temperature (20 °C) would alleviate

Table 3. Expt. 2: Influence of root hydration temperature on percent survival (any visible growth after 4 weeks), plant height (substrate line to tallest leaf after 4 or 11 weeks in greenhouse), and foliar dry weight after 11 weeks (severed at substrate line and dried 3d at 70 °C) of *Ranunculus asiaticus*.

Hydration temp (°C)	Survival (%)	Ht 4 wk (cm)	Ht 11 wk (cm)	Foliar dry wt (g)
5	36	4.7	20.7	2.99
10	50	6.1	21.7	3.72
17	69	8.4	24.4	4.03
20	89	8.0	21.9	4.77
25	56	9.7	18.8	3.48
30	83	9.2	26.2	5.62
35	56	5.9	21.5	4.36
Temp. (T)	***	**	NS	*
T $\times$ T	***	***	NS	NS

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 4. Expt. 3: Influence of root hydration temperature on percent survival (any visible growth) and plant visual quality (1 = poor; 5 = best) of *Ranunculus asiaticus* after 4 weeks in the greenhouse.

Hydration temp (°C)	Cultivar					Cultivar				
	Tecolote Pink	Labelle Cream	Tecolote Red	Tecolote White	Avg	Tecolote Pink	Labelle Cream	Tecolote Red	Tecolote White	Avg
	Survival (%)					Visual quality				
5	25	70	90	100	71	3	3	3	4	3
15	60	85	95	95	84	4	4	3	4	4
25	35	70	100	90	74	3	4	4	4	4
35	15	30	60	40	36	3	2	3	4	3
Avg	34	64	86	81	66	3	3	3	4	3
Cultivar (C)			***					NS		
Temp. (T)			***					**		
C $\times$ T			NS					NS		
T $\times$ T			***					**		
T $\times$ T $\times$ C			NS					NS		

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

Table 5. Expt. 3: Influence of root hydration temperature on plant size (mean of height and two cross canopy diameter measurements) and foliar dry weight (after 3 d at 70 °C) of *Ranunculus asiaticus* after 4 weeks in the greenhouse.

Hydration temp (°C)	Cultivar					Cultivar				
	Tecolote Pink	Labelle Cream	Tecolote Red	Tecolote White	Avg	Tecolote Pink	Labelle Cream	Tecolote Red	Tecolote White	Avg
	Size (cm)					Foliar dry wt (g)				
5	7.5	15.3	14.9	17.2	13.7	0.10	0.32	0.38	0.54	0.34
15	11.5	16.2	14.7	18.3	15.2	0.40	0.43	0.37	0.65	0.46
25	13.8	15.9	17.0	16.0	15.7	0.47	0.48	0.45	0.46	0.47
35	14.0	9.3	13.8	14.5	12.9	0.28	0.17	0.28	0.46	0.30
Avg	11.8	14.2	15.1	16.5	14.4	0.31	0.35	0.37	0.53	0.39
Cultivar (C)			***					**		
Temp. (T)			**					**		
C $\times$ T			**					NS		
T $\times$ T			**					***		
T $\times$ T $\times$ C			NS					NS		

NS, *, **, ***Nonsignificant or significant at $P \leq 0.05$, 0.01, or 0.001, respectively.

the observed problems when hydrating at low temperatures.

It is interesting that the trend for plant quality parameters was generally consistent with trends in plant survival for the first 4 weeks of growth (Tables 3 to 5). This effect appears transient, however, because those observed parameters were not significantly different at 11 weeks' growth. The number of flowers was unaffected by hydration temperature, presumably because initiation occurs after sprouting in the *R. asiaticus* growth cycle (Kamenetsky et al., 2005). Foliar dry weight followed a similar quadratic trend to plant survival after 4 weeks but increased with hydration temperature after 11 weeks. We

attribute this change in long-term growth habit to other independent factors not considered in this experiment. It could be important in future studies to determine if low hydration temperature results in a developmental delay after sprouting rather than simply a change in plant size or flower number at maturity. This information could be particularly important to forcers of geophytes.

As a result of noticeable growth habit variations among individual *R. asiaticus* plants, we were unsure if our measured parameters were adequate to describe plant growth in Expt. 1; thus, additional parameters were added with subsequent experiments. However, because plant height, size, and visual quality were

consistently supported by shoot dry weight values, it seems the measured parameters were appropriate quantifiers for *R. asiaticus* growth (Fig. 5; Tables 3 to 5).

Water temperature monitoring is an important factor when hydrating *R. asiaticus* and should be maintained between 15 and 25 °C. The common cultural recommendation to “hydrate roots via slowly running water” (De Hertogh, 1996; Umiel and Hagiladi, 1999) may result in poor results if the tap water is too cold. For instance, the temperature of tap water in our laboratory was seasonally as low as 5 °C and its maximum was 15 °C; therefore, the entire range of our tap water temperature may be too cold for optimum hydration of *R. asiaticus*. It is also possible for tap water to be too warm if the plumbing is exposed to sunlight or other heat sources, like in a greenhouse setting.

In commercial production, missing plants are expensive to replace; therefore, plant survival is probably the most important variable for determining treatment success. Once survival is optimized, quality parameters become increasingly important. Our results demonstrate that a hydration temperature between 15 and 25 °C is necessary to obtain the best quality when growing *Ranunculus asiaticus* from its dried tuberous roots.

Literature Cited

- Abu-Ghannam, N. and B. McKenna. 1997. The application of Peleg's equation to model water absorption during the soaking of red kidney beans (*Phaseolus vulgaris* L.). *J. Food Eng.* 32:391–401.
- Bello, M.O., M.P. Tolaba, and C. Suarez. 2008. Hydration kinetics of rice kernels under vacuum pressure. *J. Food Eng.* 4:1–19.
- Beruto, M., M. Fibiani, S. Rinino, R. Lo Scalzo, and P. Curir. 2009. Plant development of *Ranunculus asiaticus* L. tuberous roots is affected by different temperature and oxygen conditions during storage period. *Isr. J. Plant Sci.* 57:377–388.
- Celen, I.H., B. Kayisoglu, and S. Kayisoglu. 2008. Water absorption characteristics of apricot kernels during soaking. *J. Food Process Eng.* 31:711–720.
- Christiansen, M.N. 1968. Induction and prevention of chilling injury to radical tips of imbibing cottonseed. *Plant Physiol.* 43:743–746.
- Copeland, L.O. and M.B. McDonald. 2001. Principles of seed science and technology. 4th Ed. Kluwer Academic Publishers, Boston, MA.
- De Hertogh, A.A. 1996. Holland bulb forcer's guide. 5th Ed. Alkemade Printing BV, Lisse, The Netherlands.
- Hamrick, D. 2003. Ball redbook V2. 17th Ed. Ball Publishing, Batavia, IL.
- Hung, T.V., L.H. Liu, and R.G. Black. 1993. Water absorption in chickpea (*C. arretinum*) and field pea (*P. sativum*) cultivars using the Peleg model. *J. Food Sci.* 58:848–852.
- Kamenetsky, R., R.L. Peterson, L.H. Melville, C.F. Machado, and D. Bewley. 2005. Seasonal adaptations of the tuberous roots of *Ranunculus asiaticus* to desiccation and resurrection by changes in cell structure and protein content. *New Phytol.* 166:193–204.
- Meynet, J. 1993. *Ranunculus*, p. 603–610. In: De Hertogh, A.A., and M. Le Nard (eds.). *Physiology of flower bulbs*. Elsevier Sci. Publ., Amsterdam, The Netherlands.
- Ohkawa, K. 1986. Growth and flowering of *Ranunculus asiaticus*. *Acta Hort.* 177:165–172.
- Peleg, M. 1988. An empirical model for the description of moisture sorption curves. *J. Food Sci.* 53:1216–1217, 1219.
- Pollock, B.M. and V.K. Toole. 1966. Imbibition period as critical temperature sensitive stage in germination of lima bean seeds. *Plant Physiol.* 41:221–229.
- Powell, A.A. and S. Matthews. 1978. The damaging effect of water on dry pea embryos during imbibition. *J. Expt. Bot.* 29:1215–1229.
- Prasad, K., P.R. Vairagar, and M.B. Bera. 2010. Temperature dependent hydration kinetics of *Cicer arietinum* splits. *Food Res. Intl.* 43:483–488.
- Priestley, D.A. 1986. Seed aging: Implications for seed storage and persistence in the soil. Comstock Publishing Associates, Ithaca, NY.
- Sarchetti, G., P. Pittia, M. Biserni, G.G. Pinnaiva, and M.D. Rosa. 2003. Kinetic modeling of textural changes in ready-to-eat breakfast cereals during soaking in semi-skimmed milk. *Intl. J. Food Sci. Technol.* 38:135–143.
- Solomon, W.K. 2007. Hydration kinetics of lupin (*Lupinus albus*) seeds. *J. Food Process Eng.* 30:119–130.
- Solomon, W.K. 2009. Hydration kinetics of roasted lupin (*Lupinus albus*) seeds. *J. Food. Process. Preserv.* 33:214–225.
- Sopade, P.A., E.S. Ajisengiri, and M.H. Badau. 1992. The use of Peleg's equation to model water absorption in some cereal grains during soaking. *J. Food Eng.* 15:269–283.
- Tilden, R.L. and S.H. West. 1985. Reversal of the effects of aging in soybean seeds. *Plant Physiol.* 77:584–586.
- Tully, R.E., M.E. Musgrave, and A.C. Leopold. 1981. The seed coat as a control of imbibitional chilling injury. *Crop Sci.* 21:312–317.
- Turhan, M., S. Sayar, and S. Gunasekaran. 2002. Application of the Peleg model to study water absorption in chickpea during soaking. *J. Food Eng.* 53:153–159.
- Umiel, N. and A. Hagiladi. 1999. Preparation of *Ranunculus* corns for early flowering in 8 easy steps. Dept. Orn. Hort. Agr. Res. Org., Bet-Dagan, Israel.