

Morphological dormancy, embryo growth and pericarp restraint during crop and wild Apiaceae mericarp germination in response to ambient temperature

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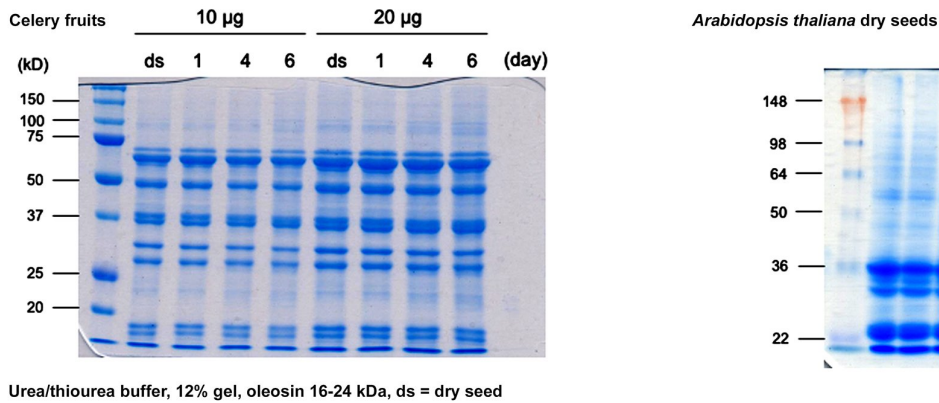
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Supplementary Information

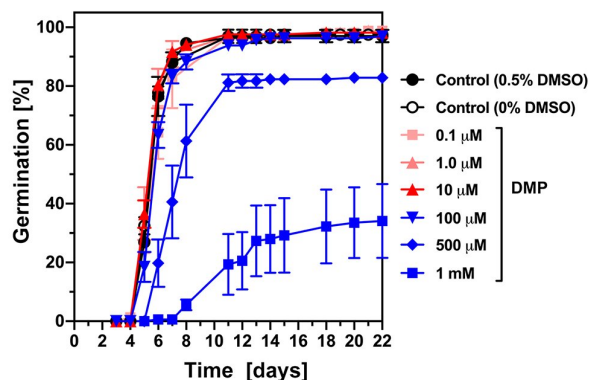
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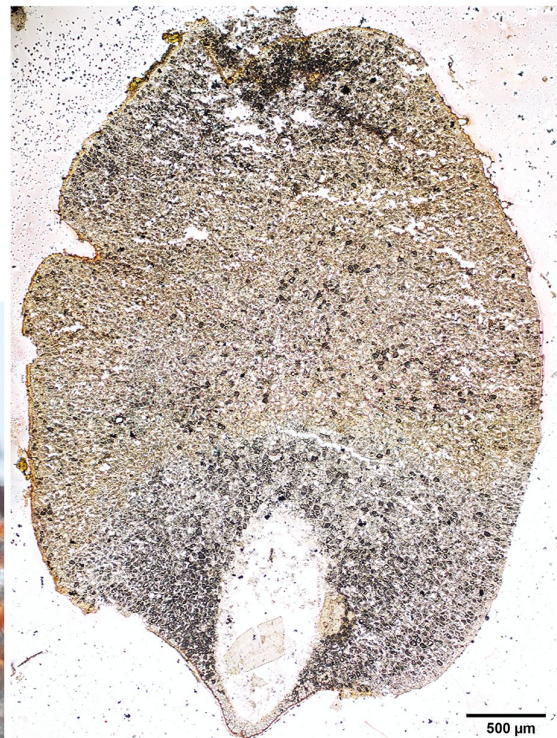
A Patterns of soluble proteins during celery fruit imbibition (SDS-PAGE)



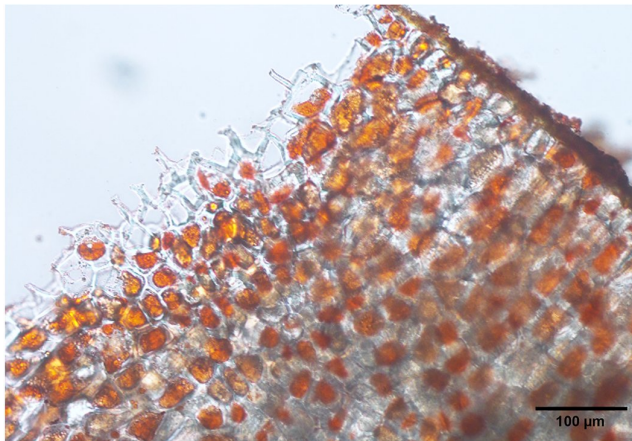
B Effects of triacylglycerol (TAG) mobilization inhibitor diphenyl methylphosphonate (DMP) on celery germination



C Lipid staining (Sudan IV) of a parsnip seed section



D Lipid staining (Sudan IV) of a parsnip endosperm section

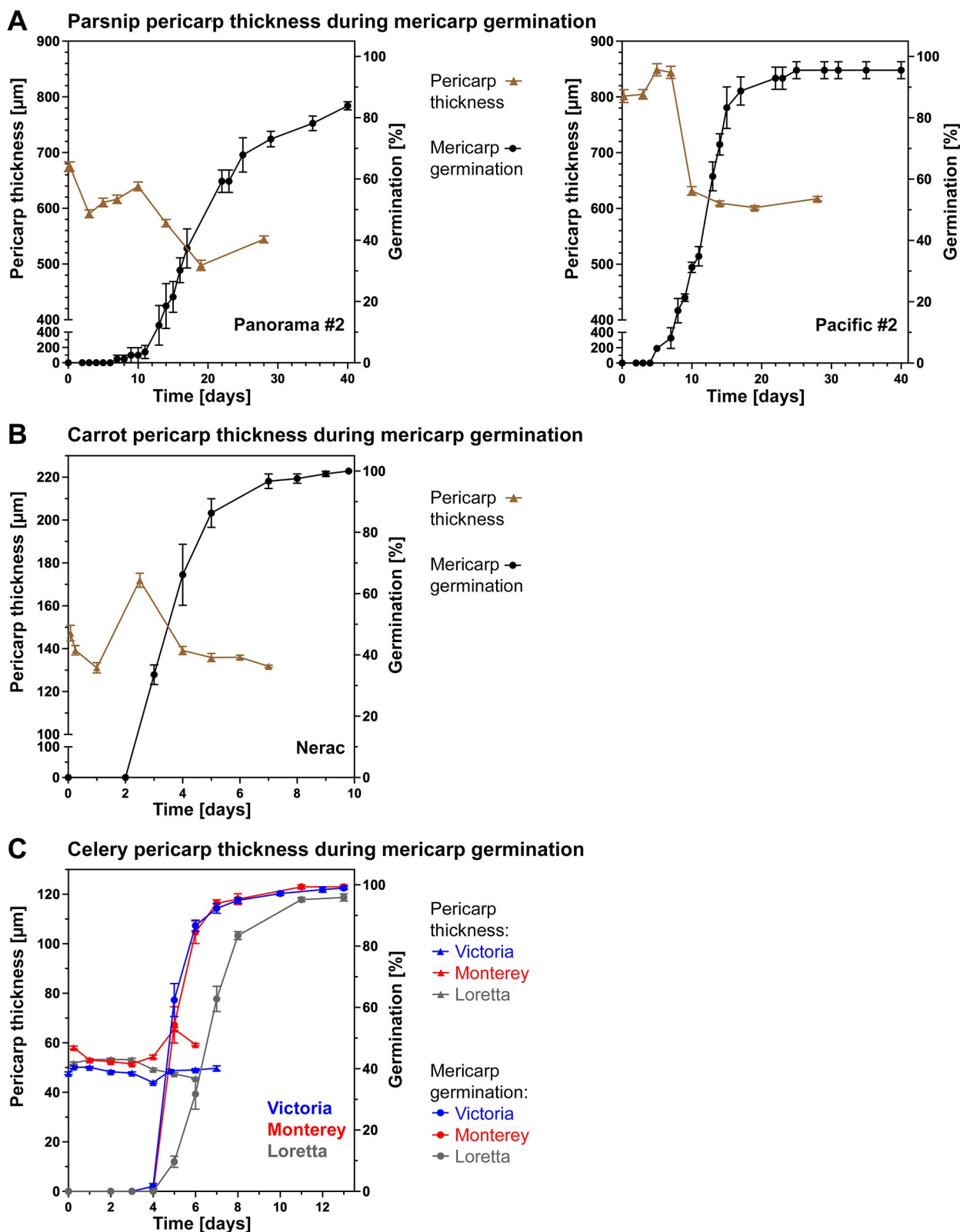


Supplementary Fig. S1. Storage protein and lipid mobilization in celery and parsnip endosperms. **(A)** SDS-PAGE analysis of soluble proteins in the endosperm during *Apium graveolens* (celery) cultivar Victoria fruit imbibition at 20°C in continuous white light. Note that the celery storage protein pattern differs considerably from *Arabidopsis thaliana* seeds which is shown for comparison.

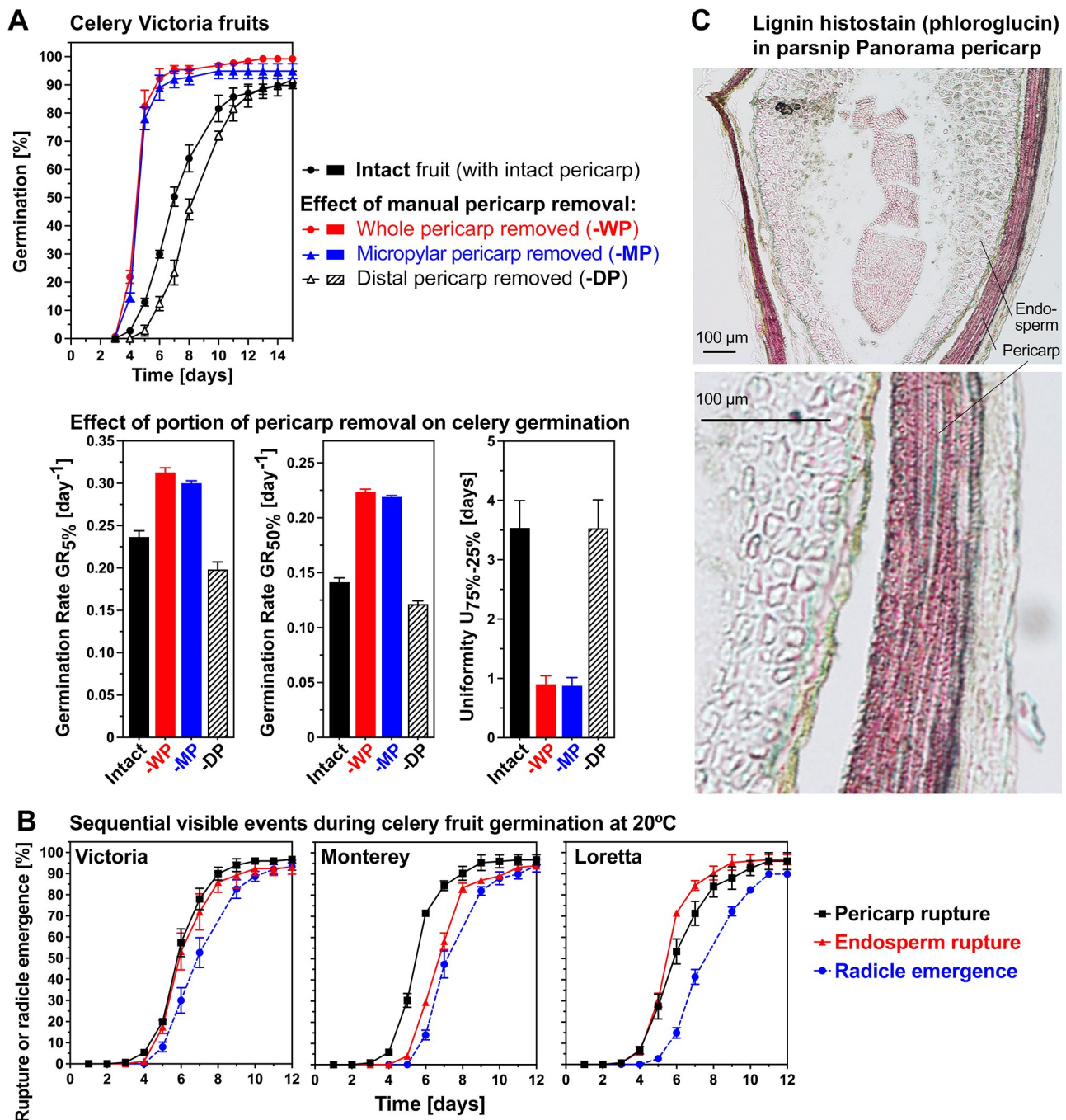
(B) Effects of the triacylglycerol (TAG) mobilization inhibitor diphenyl methylphosphonate (DMP) on the germination of imbibed Victoria fruits. DMP is known to be a fairly specific inhibitor for TAG mobilization (Brown et al., 2013). Mean $\pm$ SEM values are presented of triplicate plates each with 50 celery fruits.

(C-D) Sudan IV histological staining of lipids in *Pastinaca sativa* (parsnip) cultivar Panorama batch #3 endosperm sections. Note the stained oilbodies in the endosperm, while the small embryo in the seed section does not show comparable lipid staining.

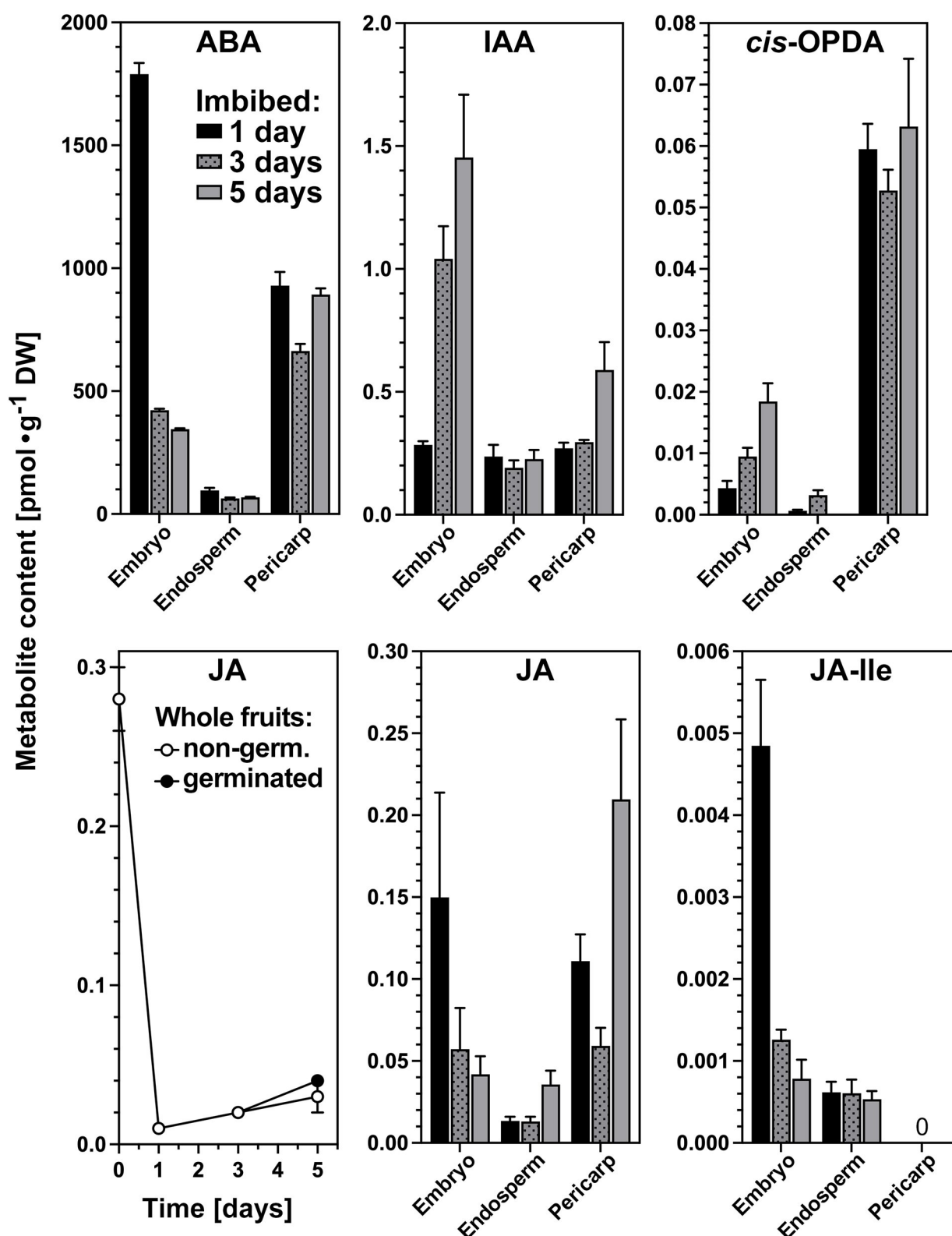
Brown, L. A., Larson, T. R., Graham, I. A., Hawes, C., Paudyal, R., Warriner, S. L., & Baker, A. (2013). An inhibitor of oil body mobilization in *Arabidopsis*. *New Phytologist*, 200, 641-649.



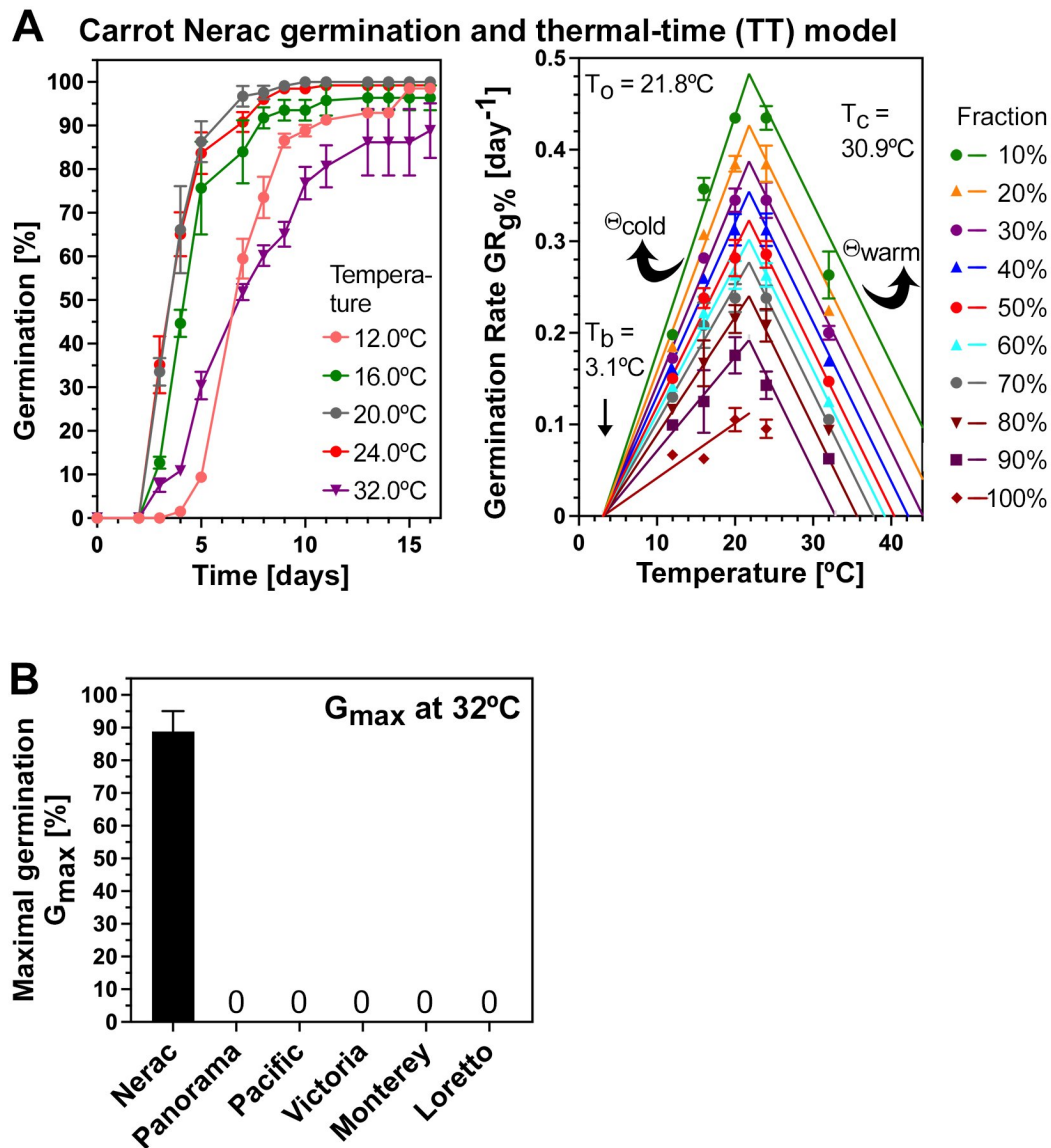
Supplementary Fig. S2. Apiaceae pericarp thickness during mericarp imbibition and germination. **(A)** Pericarp thickness and germination of imbibed parsnip cultivars Panorama and Pacific, seedlots #2. **(B)** Pericarp thickness and germination of imbibed carrot cultivar Nerac. **(C)** Pericarp thickness and germination of imbibed celery cultivars Victoria, Monterey and Loretta. Imbibition conditions: 20°C, continuous light; Mean $\pm$ SEM of three replicate plates each with 30 (parsnip) or 50 (carrot, celery) fruits. Note that the pericarp thickness differs considerably between the crop species.



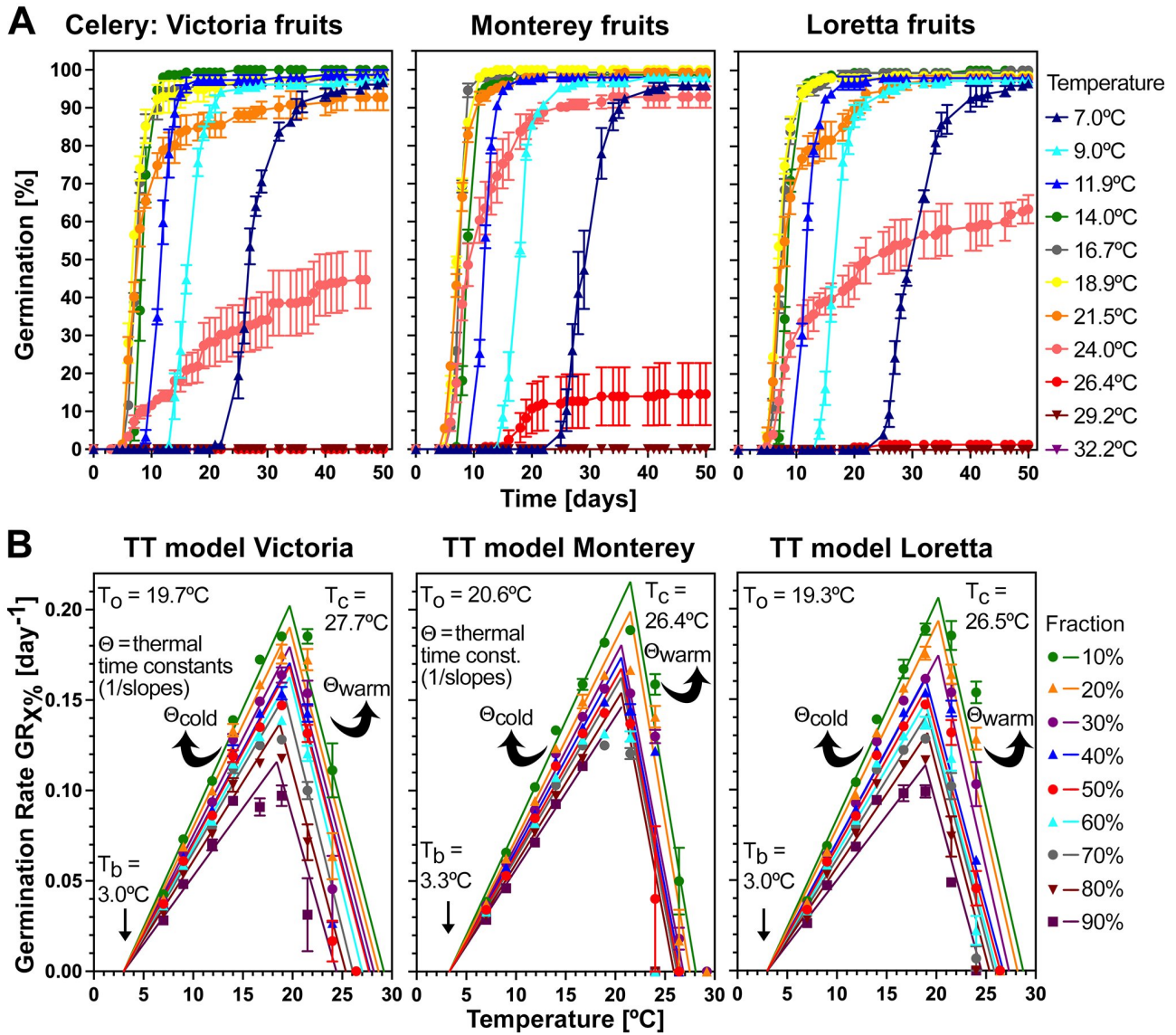
Supplementary Fig. S3. Roles and properties of the Apiaceae pericarp as germination constraint. **(A)** Pericarp ablation experiments with celery cultivar Victoria fruits imbibed (20 °C in continuous light) with intact (control) pericarp or with a portion (as indicated) of the pericarp removed. Germination, including onset (germination rate GR_{5%}, i.e. the inverse of the time to reach 5% germination) speed (GR_{50%}, i.e. the inverse of the time to reach 50% germination) and uniformity (U_{75%-25%} which is the time difference for the populations to reach 25% and 75% germination); note that low U_{75%-25%} values therefore indicate high germination uniformity. Note that removal of the micropylar pericarp, but not the distal pericarp, affected celery fruit germination. **(B)** Rupture of pericarp and endosperm as sequential visible events during the germination of celery fruits of three cultivars. Mean values ± SEM are presented for triplicate plates each with 50 fruits. **(C)** Lignin histostaining (phloroglucinol) of parsnip Panorama #3 fruit sections. Note that the pericarp stains heavily for lignin which is detected in different layers of the pericarp.



Supplementary Fig. S4. Spatiotemporal hormonal analysis of celery cultivar Victoria germination during imbibition at 20°C in continuous white light. Metabolite contents per dry weight (DW) in dry and imbibed fruits and fruit compartments (embryo, endosperm, pericarp) at different times. ABA, abscisic acid; IAA, indole-3-acetic acid; JA, jasmonic acid; JA-Ile, jasmonoyl-L-isoleucine; *cis*-OPDA, *cis*-(+)-12-oxo-phytodienoic acid. Mean $\pm$ SEM values are presented obtained from five biological replicates with $\sim$ 100 fruits used per replicate sample. Note that the hormone contents in celery fruit compartments differ considerably from parsnip fruit compartments (Figures 4 and S3) especially in the pericarp for which ABA, IAA and *cis*-OPDA were >3 -fold, $\sim$ 1,000-fold $\sim$ 400,000-fold lower in celery when compared to parsnip dry fruits.



Supplementary Fig. S6. The effect of temperature mericarp germination of *Daucus carota* (carrot) and other Apiaceae. (A) Responses to different imbibition temperatures (*left panel*) and population-based thermal-time threshold modelling (*right panel*) of carrot cultivar Nerac germination in continuous white light. The thermal-time model delivered estimated cardinal temperatures T_b (base), T_o (optimal), T_c (ceiling or maximal) in °C and the thermal-time constants Θ_{cold} and Θ_{warm} in °C•days (derived from the slopes of the regression lines; see the material and method section for details) are indicated in the figure and listed in Table 1. (B) Maximal germination percentages ($G_{\max}$) of carrot (cultivar Nerac), parsnip (cultivars Panorama and Pacific) and celery (cultivars Victoria, Monterey, and Loretto) at 32°C. Note that thermoinhibition blocked the germination of all parsnip and celery batches. In contrast to this, carrot cultivar Nerac germinated readily when imbibed at 32°C. Mean $\pm$ SEM germination values presented are from triplicate plates each with 50 (celery, carrot) or 30 (parsnip) fruits.



Supplementary Fig. S7. Comparative germination analysis of *Apium graveolens* temperature responses. (A) The effect of different imbibition temperatures on the germination of fruits of the three celery cultivars Victoria, Monterey and Loretta in continuous white light. Mean $\pm$ SEM values are presented for triplicate plates each with 50 fruits. (B) Population-based thermal-time (TT) threshold modelling of corresponding fruit and seed germination. The TT models delivered estimated cardinal temperatures T_b (base), T_o (optimal), T_c (ceiling or maximal) in $^{\circ}\text{C}$ and the thermal-time constants Θ_{cold} and Θ_{warm} in $^{\circ}\text{C}\cdot\text{days}$ (derived from the slopes of the regression lines; see the material and method section for details) as indicated in the figure and listed in Table 1.

Supplementary Table S1. Morphological mericarp (fruit) and seed properties of Apiaceae cultivars.

Species	Cultivar	Batch	Number	Grading [mm]	Mass TSW [g]	Entity	Length $\pm$ SEM [mm]
Parsnip	Panorama	#1	E64291	4.75-5.00	5.810	Fruit	5.581 $\pm$ 0.083
						Seed	4.514 $\pm$ 0.071
Parsnip	Panorama	#2	E57306	4.75-5.00	6.725	Fruit	5.623 $\pm$ 0.101
						Seed	4.572 $\pm$ 0.077
Parsnip	Pacific	#1	E64292	4.75-5.00	6.215	Fruit	6.095 $\pm$ 0.071
						Seed	4.821 $\pm$ 0.057
Parsnip	Pacific	#2	E57305	4.75-5.00	6.471	Fruit	5.979 $\pm$ 0.081
						Seed	4.805 $\pm$ 0.065
Parsnip	Panorama	#3	E38814	4.75-5.00	4.540	Fruit	4.900 $\pm$ 0.096
						Seed	4.095 $\pm$ 0.047
Parsnip	Panorama	#3	E38817	3.75-4.00	6.880	Fruit	6.079 $\pm$ 0.079
						Seed	3.397 $\pm$ 0.066
Celery	Victoria		03731094		0.310	Fruit	1.243 $\pm$ 0.011
						Seed	1.138 $\pm$ 0.011
Celery	Monterey		03731245		0.350	Fruit	1.168 $\pm$ 0.010
						Seed	1.061 $\pm$ 0.009
Celery	Loretta		037245382		0.280	Fruit	1.222 $\pm$ 0.011
						Seed	1.121 $\pm$ 0.011
Carrot	Nerac		E56490	1.6-1.8	1.007	Fruit	2.556 $\pm$ 0.040
						Seed	2.303 $\pm$ 0.037

Table S2. Relative embryo sizes of wild and cultivated Apiaceae species; EL, embryo length; E:F, embryo:fruit length ratio. The dataset is organised by phylogenetic groups A, B and others (Figure 2), type (crop, wild species, or landrace) and Apiaceae tribe (Walker et al. 2021). Original literature resources are provided; note that for original literature marked with “*”, the data were obtained from the supplementary data of (Visscher et al. 2022).

Species name (and details)	Type	Group	Apiaceae tribe	Initial EL [mm]	Critical EL [mm]	Fruit length [mm]	Initial E:F ratio	Critical E:F ratio	Literature sources
<i>Pastinaca sativa</i> cv. Pacific #1	Crop	A	Tordylieae	1.67	3.45	6.10	0.274	0.567	This work
<i>Pastinaca sativa</i> cv. Pacific #2	Crop	A	Tordylieae	1.55	3.48	5.98	0.259	0.582	This work
<i>Pastinaca sativa</i> cv. Panorama #1	Crop	A	Tordylieae	1.45	3.00	5.58	0.259	0.538	This work
<i>Pastinaca sativa</i> cv. Panorama #2	Crop	A	Tordylieae	1.19	3.04	5.62	0.212	0.541	This work
<i>Apium graveolens</i> cv. Victoria	Crop	A	Apieae	0.32	1.01	1.24	0.255	0.812	(Walker et al. 2021)
<i>Apium graveolens</i> cv. Monterey	Crop	A	Apieae	0.30	0.95	1.17	0.255	0.813	This work
<i>Apium graveolens</i> cv. Loretta	Crop	A	Apieae	0.32	1.01	1.22	0.259	0.825	This work
<i>Foeniculum vulgare</i> cv. Fasa and cv. Chahestan ^a	Crop	A	Apieae	1.16	2.41	4.36	0.263	0.567	(Hashemirad et al. 2023)
<i>Anethum graveolens</i> cv. Kentavr ^a	Crop	A	Apieae	0.93	2.45	3.28	0.281	0.743	(Bukharov et al. 2021)
<i>Anethum graveolens</i> cv. Centaur ^a	Crop	A	Apiaae	0.85	2.45	3.35	0.260	0.730	(Soldatenko et al. 2020)
<i>Hladnikia pastinacifolia</i>	Wild	A	Careae	0.55	2.81	3.35	0.164	0.840	(Sajna et al. 2019)*
<i>Aegopodium podagraria</i>	Wild	A	Careae	0.35	2.86	2.96	0.138	0.965	(Vandelook et al. 2009)*
<i>Sison amomum</i>	Wild	A	Pyramidoptereae	2.10	4.92	6.00	0.350	0.820	(Van Assche et al. 2011)*
<i>Cyclospermum leptophyllum</i>	Wild	A	Pyramidoptereae	0.34	1.22	1.25	0.272	0.976	(Walck et al. 2008)*
<i>Elwendia caroides</i>	Wild	A	Pyramidoptereae	0.96	4.17	5.96	0.160	0.699	(Rahimi et al. 2024)
<i>Elwendia wolfii</i>	Wild	A	Pyramidoptereae	0.28	3.44	4.04	0.070	0.850	(Rahimi et al. 2024)
<i>Bunium persicon</i> (mean of four populations)	Wild	A	Pyramidoptereae				0.162	0.775	(Mohammadianfar et al. 2024)
<i>Angelica keiskei</i>	Wild	A	Selineae	2.31	9.07	10.67	0.216	0.850	(Zhang et al. 2019)*
<i>Angelica sylvestris</i>	Wild	A	Selineae	0.50	0.78	4.73	0.200	0.700	(Vandelook et al. 2007a)
<i>Selinum carvifolia</i>	Wild	A	Selineae	0.46	2.46	2.95	0.300	0.834	(Vandelook et al. 2007a)
<i>Thaspium pinnatifidum</i>	Wild	A	Selineae	0.70	3.60	4.00	0.175	0.900	(Baskin et al. 1992)*
<i>Lomatium dissectum</i>	Wild	A	Selineae	1.35	7.40	9.00	0.123	0.820	(Scholten et al. 2009)
<i>Saposhnikovia divaricata</i>	Wild	A	Selineae	0.96		5.66	0.171		(Yugrina et al. 2021)
<i>Glehnia littoralis</i>	Wild	A	Selineae	1.04		6.55	0.150		(Yeom et al. 2021)
<i>Heracleum sphondylium</i>	Wild	A	Tordylieae	1.00	4.00	5.01	0.094	0.798	(Stokes 1952)*
<i>Pastinaca sativa</i> (wild parsnip) ^b	Wild	A	Tordylieae	0.82	4.75		0.173		(Hendrix et al. 1991)*
<i>Conium maculatum</i>	Wild	A	<i>Conium</i> clade	0.90	1.70	2.77	0.325	0.614	(Baskin and Baskin 1990b)*
<i>Prangos ferulacea</i>	Wild	A	<i>Cachrys</i> clade	3.50	7.00	12.00	0.292	0.583	(Razavi and Hajiboland 2009)*

Species name (and details)	Type	Group	Apiaceae tribe	Initial EL [mm]	Critical EL [mm]	Fruit length [mm]	Initial E:F ratio	Critical E:F ratio	Source
<i>Daucus carota</i> cv. Nerac	Crop	B	Daucinae	0.85	2.00	2.56	0.334	0.786	This work
<i>Daucus carota</i> cv. Chanteney ^c	Crop	B	Daucinae	1.34		3.37	0.401		(Gray et al. 1988)
<i>Cuminum cyminum</i> (mean of 15 Iranian and Indian landraces)	Landr.	B	Daucinae	1.42		5.16	0.274		(Soltani et al. 2019)
<i>Daucus carota</i> (mean of 16 wild carrot accessions from Europe)	Wild	B	Daucinae				0.328		(Vandelook et al. 2024)
<i>Daucus carota</i> (mean of 24 wild carrot accessions from North America)	Wild	B	Daucinae				0.249		(Vandelook et al. 2024)
<i>Pterygopleurum neurophyllum</i>	Wild	B	<i>Acronema</i> clade	0.23	0.99	2.42	0.096	0.411	(Kwon et al. 2020)*
<i>Smyrniium cordifolium</i>	Wild	B	Smyrnieae				0.200	0.820	(Zarei-Gavkosh et al. 2022)
<i>Bubon macedonicum</i>	Wild	B	Daucinae	0.60	1.67	1.81	0.334	0.924	(Di Cecco et al. 2018)*
<i>Ferula gummosa</i>	Wild	B	Ferulinae	1.70	3.35	5.05	0.337	0.663	(Zardari et al. 2019)*
<i>Ferula ovina</i>	Wild	B	Ferulinae	3.33	8.19	9.00	0.370	0.910	(Fasih and Afshari 2018)*
<i>Osmorhiza longistylis</i>	Wild	B	Scandicinae	0.60	8.80	13.40	0.062	0.657	(Baskin et al. 1995)*
<i>Osmorhiza aristata</i>	Wild	B	Scandicinae	0.48	9.00	11.10	0.043	0.811	(Walck et al. 2002)*
<i>Osmorhiza depauperata</i>	Wild	B	Scandicinae	0.58	9.00	9.62	0.060	0.936	(Walck and Hidayati 2004)*
<i>Osmorhiza occidentalis</i>	Wild	B	Scandicinae	1.22	9.40	10.00	0.122	0.940	(Baskin et al. 1995)*
<i>Osmorhiza aristata</i> var. <i>aristata</i>	Wild	B	Scandicinae	0.50	9.80	10.30	0.049	0.951	(Baskin and Baskin 1991)*
<i>Osmorhiza chilensis</i>	Wild	B	Scandicinae	0.60	9.20	9.50	0.063	0.968	(Baskin et al. 1995)*
<i>Chaerophyllum aureum</i>	Wild	B	Scandicinae	1.07	4.80	8.03	0.133	0.598	(Santiago et al. 2019)*
<i>Chaerophyllum tainturieri</i>	Wild	B	Scandicinae	0.47	2.80	4.00	0.107	0.700	(Baskin and Baskin 1990a)*
<i>Chaerophyllum bulbosum</i>	Wild	B	Scandicinae	0.50	3.55	4.64	0.108	0.765	(Janiesch 1971)*
<i>Chaerophyllum procumbens</i>	Wild	B	Scandicinae	0.50	4.60	5.00	0.100	0.920	(Baskin and Baskin 1990a)*
<i>Chaerophyllum temulum</i>	Wild	B	Scandicinae	0.53	3.24	3.41	0.156	0.950	(Vandelook et al. 2007b)
<i>Anthriscus sylvestris</i>	Wild	B	Scandicinae	0.45	4.57	5.00	0.090	0.914	(Baskin et al. 2000)*
<i>Conopodium majus</i>	Wild	B	Scandicinae	0.30	2.09	2.22	0.135	0.941	(Blandino et al. 2019)*
<i>Torilis japonica</i>	Wild	B	Torilidinae	0.25	0.93	2.25	0.111	0.413	(Vandelook et al. 2008)*
<i>Torilis scabra</i>	Wild	B	Torilidinae	1.10	3.30	4.78	0.230	0.690	(Zhang et al. 2023)
<i>Turgenia latifolia</i>	Wild	B	Torilidinae	3.99	8.30	10.51	0.380	0.790	(Nurulla et al. 2014)*

Species name (and details)	Type	Group	Apiaceae tribe	Initial EL [mm]	Critical EL [mm]	Fruit length [mm]	Initial E:F ratio	Critical E:F ratio	Source
<i>Cicuta virosa</i>	Wild	Other	Oenantheae	0.33	0.92	1.95	0.170	0.469	(Cho et al. 2018)*
<i>Trepocarpus aethusae</i>	Wild	Other	Oenantheae	1.81	4.16	8.00	0.064	0.520	(Baskin et al. 2003)*
<i>Cryptotaenia canadensis</i>	Wild	Other	Oenantheae	1.60	3.00	4.81	0.333	0.624	(Baskin and Baskin 1988)*
<i>Perideridia americana</i>	Wild	Other	Oenantheae	0.30	2.80	3.00	0.100	0.933	(Baskin and Baskin 1993)*
<i>Ptilimnium nutallii</i>	Wild	Other	Oenantheae	0.22	1.25	1.26	0.175	0.992	(Baskin et al. 1999)*
<i>Bupleurum kakiskalae</i>	Wild	Other	Bupleureae	0.57	1.51	1.89	0.300	0.800	(Visscher et al. 2022)
<i>Sanicula trifoliata</i>	Wild	Other	Saniculeae	0.50	2.99	6.00	0.083	0.498	(Hawkins et al. 2010)*
<i>Sanicula canadensis</i>	Wild	Other	Saniculeae	0.36	1.58	2.00	0.123	0.790	(Hawkins et al. 2010)*
<i>Sanicula gregaria</i>	Wild	Other	Saniculeae	0.38	2.54	3.00	0.127	0.847	(Hawkins et al. 2010)*
<i>Sanicula europaea</i>	Wild	Other	Saniculeae	0.32	2.10	2.38	0.136	0.883	(Vandelook and Van Assche 2008)*
<i>Eryngium sparanophyllum</i>	Wild	Other	Saniculeae	0.55	1.51	2.42	0.236	0.602	(Wolkis et al. 2020)
<i>Eryngium yuccifolium</i>	Wild	Other	Saniculeae	0.98	2.86	3.01	0.326	0.950	(Schutte and Knee 2005)*
<i>Eryngium viviparum</i>	Wild	Other	Saniculeae	0.42	1.00	1.03	0.310	0.978	(Ayuso et al. 2017)

^a To calculate seed length (S) from the fruit length results in the table, and from there E:S ratios presented in Figure 8D, the thickness of the pericarp data for these species published by Ma *et al.* (2015) was used. For *Anethum graveolens* mean $\pm$ SEM of primary and secondary umbels, and for *Foeniculum vulgare* mean $\pm$ SEM of two cultivars are presented.

^b Fruit length was calculated from the fruit mass data presented in Figure 1 of Hendrix *et al.* (1991) based on a linear relationship ($R^2 = 0.74$) between fruit mass and fruit length data of cultivated parsnip fruits (Supplementary Table S1); the E:F ratio is the mean $\pm$ SEM (0.173 ± 0.004) calculated from 72 datapoints for wild parsnip collected from a pasture in Iowa (Hendrix *et al.* 1991).

^c Fruit length was calculated from the fruit mass data presented in Table 2 of Gray *et al.* (1988) based on a linear relationship ($R^2 = 0.92$) between fruit mass and fruit length data of carrot cultivar Nerac (Supplementary Table S1) plus data from 10 wild carrot accessions fruits (Kadluczka and Grzebelus 2022); results are supported by several publications by Gray *et al.* (1988; 1984) on this carrot cultivar.

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