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'UC Eclipse', a Summer Plant-adapted Photoperiod-insensitive Strawberry Cultivar

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'UC Eclipse', a photoperiod-insensitive cultivar of strawberry (*Fragaria ×ananassa* Duchesne), was developed and released by the University of California, Davis (UC Davis) College of Agriculture & Environmental Sciences for summer-plant production. The colloquial "summer-plant" designation has been adopted in California agriculture to distinguish summer- from autumn-planted production of day-neutral cultivars. The development of productive day-neutral cultivars has played a significant role in the evolution and expansion of strawberry production in California, starting with the release of an initial series of photoperiod-insensitive day-neutral cultivars in 1980 ('Aptos', 'Brighton', and 'Hecker') that effectively doubled the length of the harvest season, and complemented the seasonal production of photoperiod-sensitive short-day cultivars (Bringhurst and Voth 1980). The development of 'Portola', a "day-neutral" cultivar adapted for summer-plant production, 27 years later further widened the harvest season and greatly increased the supply of fresh strawberries in months of the year when production was historically more limited.

The summer-plant segment has been expanding in California to meet the demand for fresh strawberries in autumn markets and complement the production of autumn-planted short-day and day-neutral cultivars. Summer-plant cultivars are most often planted in June or July in coastal California production districts where autumn-planted short-day cultivars are grown, from San Diego (32.7°N) to Santa Maria (35.0°N). Summer-plant cultivars are annually planted in California plasticulture production systems using bare-root plants (stolon-propagated clones) propagated in low-elevation nurseries (e.g., Turlock, CA; 31 m; 37.3°N) that are harvested in the winter and stored at −2.0 °C until planting (colloquially known as "frigo plants"). Although 'UC Eclipse' was originally developed for summer-plant production and other contraseason open-field and protected-culture production systems, this cultivar can be grown anywhere day-neutral cultivars are adapted. That encompasses the coastal California production districts between Santa Maria and Watsonville (36.9°N) where day-neutral cultivars are commonly planted in October using bare-root plants propagated in high-elevation nurseries (e.g., Dorris, CA; 1294 m; 42.0°N).

'UC Eclipse' has consistently produced high yields of large, firm, long shelf life fruit in open-field summer-plant production trials on commercial farms in California (Fig. 1, Tables 1 and 2). Here we show that the cumulative marketable fruit yields of 'UC Eclipse' are substantially greater than 'Portola' (#US20090144866P1), currently the most widely grown summer-plant cultivar in California (Tables 1 and 2). 'UC Eclipse' and 'Portola' are heterozygous for *FW1*, a dominant gene that confers resistance to Fusarium wilt race 1, a disease caused by the prevalent race of *Fusarium oxysporum* f.sp. *fragariae* currently found in California (Henry et al. 2017, 2021; Pincot et al. 2018, 2022). The deployment of Fusarium wilt race 1 resistant cultivars has become increasingly critical in California since outbreaks of the disease were first reported in 2005 (Koike et al. 2009; Koike and Gordon 2015).

'Portola' and other photoperiod-insensitive cultivars previously developed and released by UC Davis are heterozygous for *PERPETUAL FLOWERING* (*PF*), a dominant gene that mediates photoperiod-insensitive flowering under a wide range of latitudes and temperatures (Ahmadi et al. 1990; Bringhurst et al. 1989). The *PF* gene was originally introduced into cultivated strawberry in the 1950s from 'Wasatch', a photoperiod-insensitive ecotype of *Fusarium virginiana* subsp. *glauca* native to a high-elevation habitat in the Wasatch Mountains of Utah (Bringhurst and Voth 1980). The *PF* gene is necessary and sufficient for photoperiod-insensitive flowering (Ahmadi et al. 1990; Bringhurst et al. 1989) and is necessary but not wholly sufficient for adaptation to summer-plant production. 'UC Eclipse' was selected for dependable fruit production over the range of photoperiods and temperatures encountered in coastal California summer-plant

Fig. 1. 'UC Eclipse' plants and fruit.

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Table 1. Within-trial estimated marginal means (EMMs) for cumulative marketable fruit yield of 'UC Eclipse' and check cultivars grown on farms in coastal California locations over 3 years (2019–21).

Location[i]	Yr	UC Eclipse yield (kg/ha)	Check cultivar	Check cultivar yield (kg/ha)	Yield difference (kg/ha)[ii]	Yield difference (%)[iii]	t[iv]	P value[v]
Nipomo	2019	73,537	Portola	53,032	20,505	38.7	3.3	0.02
			UCD Finn	56,815	16,723	29.4	2.7	0.04
			UCD Mojo	65,941	7,596	11.5	1.2	0.28
Ventura	2019	30,385	Portola	22,147	8,238	37.2	3.1	0.03
			UCD Finn	23,342	7,043	30.2	2.6	0.05
			Mojo	24,927	5,459	21.9	2.0	0.10
Nipomo	2020	61,261	Portola	18,917	42,344	223.9	117.7	<0.0001
			UCD Finn	33,827	27,434	44.8	81.1	<0.0001
			UCD Mojo	30,696	30,564	49.9	90.6	<0.0001
Nipomo	2020	49,255	Portola	33,434	15,910	47.7	9.8	<0.0001
			UCD Finn	41,154	8,099	30.3	4.9	0.0004
			UCD Mojo	39,902	9,351	32.9	5.8	0.0001
Santa Maria	2020	32,955	Portola	22,306	10,649	47.7	5.4	0.01
			UCD Finn	25,298	7,658	12.7	3.9	0.03
			UCD Mojo	24,795	8,160	13.5	4.1	0.03
Nipomo	2021	88,994	Portola	59,393	29,602	49.8	16.8	<0.0001
			UCD Finn	53,149	35,846	67.4	28	<0.0001
			UCD Mojo	72,813	16,182	22.2	23.4	<0.0001

[i] The Santa Maria 2020 trial was grown using organic production practices. The other trials were grown using conventional production practices. Trials were grown on two different Nipomo farms in 2020.

[ii] Yield differences (kg/ha) were estimated by linear contrasts ($EMM_E - EMM_C$) between estimated marginal means for 'UC Eclipse' (EMM_E) and check cultivars (EMM_C).

[iii] Yield difference percentages were estimated by $(EMM_E - EMM_C)/EMM_C \times 100$.

[iv] t-statistics for linear contrasts between the EMMs for 'UC Eclipse' and check cultivars.

[v] The probability of a greater t-statistic by chance for the null hypothesis of no difference between EMMs for 'UC Eclipse' and check cultivars.

production districts. This cultivar was primarily released to meet the need for a high-yielding, Fusarium wilt−resistant, long shelf life cultivar for the summer-plant segment.

Origin

'UC Eclipse' is an asexually propagated hybrid individual from a full-sib family (17C242) originating from a cross (01C206P005/12C166P002) between 01C206P005 ('Portola') and 12C166P002 ('UCD Mojo'; #USPP34265P2). The cross was produced in the winter of 2017. The pedigree for 'UC Eclipse' is depicted in Fig. 2. Clones (daughter plants) of 'UC Eclipse' were asexually propagated from stolons of the original mother plant (hybrid individual) selected among seed-propagated 01C206P005/12C166P002 individuals grown and phenotyped at the UC Davis Wolfskill Experiment Orchard (WEO), Winters, CA, in 2018. 'UC Eclipse' (an asexually propagated hybrid individual) has since been preserved by annual cycles of asexual propagation at WEO.

'UC Eclipse' was internally and externally tested as 17C242P023. Seeds of the 01C206P005/12C166P002 family were harvested from greenhouse-grown plants in the spring of 2017, germinated in Jun 2017, transplanted to a greenhouse in Jul 2017, hardened off in a shade house in Aug 2017, and transplanted to the field in Sep 2017 at WEO. Offspring of 01C206P005/12C166P002 were phenotyped in the spring of 2018 to a) identify individuals with outstanding fruit size, firmness, symmetry, color, gloss, and visual

Table 2. Across-trial estimated marginal means (EMMs) for cumulative marketable fruit yield and fruit quality traits of 'UC Eclipse' and check cultivars grown on farms in coastal California locations over 3 years (2019–21).

Trait[i]	Check cultivar	UC Eclipse EMM	Check cultivar EMM	t[ii]	P value[iii]
Yield (kg/ha)	Portola	73,096	47,360	2.5	0.02
	UCD Finn		42,702	2.9	0.01
	UCD Mojo		46,674	2.5	0.02
Weight (g/fruit)	Portola	30.2	26.3	6	<0.0001
	UCD Finn		24.0	8.9	<0.0001
	UCD Mojo		26.5	6.4	<0.0001
Firmness (g-force)	Portola	315.4	302.1	2.1	0.07
	UCD Finn		384.6	−9.8	<0.0001
	UCD Mojo		384.3	−9.8	<0.0001
TSS (%)	Portola	7.5	8.0	−3.8	0.01
	UCD Finn		8.4	−6.4	0.002
	UCD Mojo		8.5	−7.5	0.001
TA (%)	Portola	0.7	0.8	−3.1	0.03
	UCD Finn		0.6	6.4	0.01
	UCD Mojo		0.8	−1.2	0.31
TSS/TA	Portola	10.1	10.1	−0.1	0.92
	UCD Finn		13.2	−10.3	0.001
	UCD Mojo		11.1	−3.5	0.03

[i] Cumulative marketable fruit yields were estimated from fruit harvested once or twice weekly over the entire summer-plant growing season within each of the six farm × year trials (see Table 1). Fruit firmness, total soluble solids (TSS), and titratable acidity (TA) were measured from multiple fruit/replication sampled from two harvests/trial. Firmness was recorded in grams of force (g-force) using a handheld penetrometer (QA Supplies Model FT02) with a 3-mm probe. EMMs and test statistics were estimated from observations across six on-farm trials.

[ii] t-statistics for linear contrasts between the EMMs for 'UC Eclipse' and check cultivars.

[iii] The probability of a greater t-statistic by chance for the null hypothesis of no difference between two EMMs.

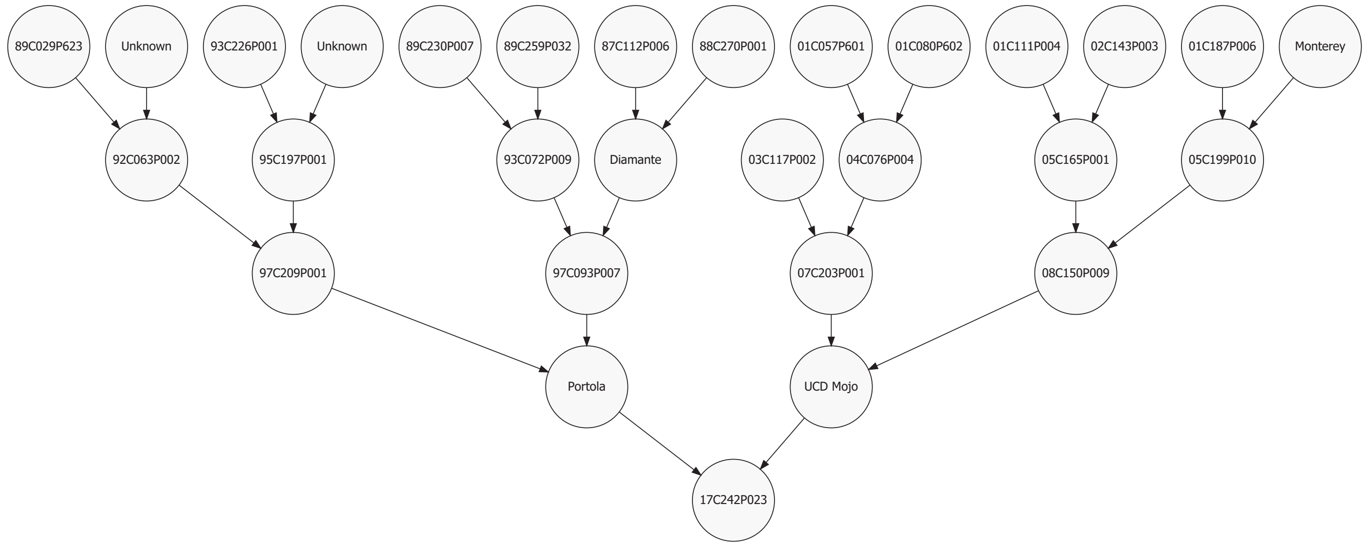

Fig. 2. Five-generation pedigree for 'UC Eclipse'.

appeal; b) eliminate individuals with fruit defects and deformities; c) estimate marketable fruit yields; d) identify photoperiod-insensitive individuals; and e) assess runner production and plant architecture. The 'UC Eclipse' mother plant (17C242P023) and 24 additional hybrids from the 2017–18 selection cycle were selected in Jun 2018 for advanced testing in the summer-plant segment.

We applied marker-assisted selection to DNA samples isolated from seedlings to identify and select 01C206P005/12C166P002 individuals that were either heterozygous or homozygous for dominant *FW1* and *PF* alleles (Ahmadi et al. 1990; Pincot et al. 2018, 2022). DNA samples of 17C242 individuals were genotyped with Kompetitive allele specific primer (KASP) markers for single nucleotide polymorphisms (SNPs) in linkage disequilibrium with *FW1* and *PF* (Pincot et al. 2022; Famula RA, unpublished data). The genotypes predicted by *PF*- and *FW1*-associated KASP-SNP markers for 'UC Eclipse' were *PFPF* and *FW1fw1*, respectively.

'UC Eclipse' and check cultivars were field tested on commercial farms in Nipomo (35.0°N), Ventura (34.3°N), and Santa Maria, CA over three summer-plant growing seasons (Tables 1 and 2). The bare-root clones for advanced testing were propagated in low-elevation nurseries using standard commercial bare-root plant production and harvest practices and postharvest chilling treatments optimized for the summer-plant market segment. Clones for the first year of testing (2018–19) were produced at WEO. Clones for subsequent years of testing (2019–20, 2020–21, and 2021–22) were produced in low-elevation nurseries operated by Lassen Canyon Nursery (Manteca, CA). Clones were harvested in January, trimmed, and stored at −2 °C until planting in the summer.

We field tested 'UC Eclipse' with 24 other hybrids (selection candidates) in 2019 and eight other hybrids in 2020 and 2021 (Table 1). These trials were planted on commercial strawberry farms and managed according to the production practices of individual growers. Soils were either flat-fumigated with Pic-Clor 60 (Cardinal Professional Products, Woodland, CA) at a rate of 500 lb/acre or drip-fumigated with Triform 80 at a rate of 15 gallons/acre. There was minimal pressure from diseases caused by soilborne pathogens on these farms, including the lone organic farm where these cultivars were tested. Hybrids and check cultivars were arranged in randomized complete block experimental designs in 2019 and 2020 and a completely randomized experimental design in 2021. The summer-plant check cultivars 'Portola', 'UCD Mojo', and 'UCD Finn' (#USPP34242P2) were tested in every trial (Table 1). Although 'UCD Mojo' and 'UCD Finn' are susceptible to Fusarium wilt race 1, they were used as checks because they were previously shown to produce firmer and sweeter fruit than 'Portola', a finding substantiated by our on-farm testing (Table 2). Hybrids were grown in two 20-plant plots in 2019 and 2020 and 500- to 1000-plant strips in 2021 (yield data were collected from two 50-plant blocks within each 500–1000 plant strip). Over the course of advanced testing, yield data were collected from eighty-four 20- or 50-plant plots grown in six summer-plant year × location trials (Table 1). Hybrids were planted between 15 May and 15 Jun in Nipomo and Santa Maria and between 1 and 15 Jul in Ventura. The number of harvests ranged from 14 to 26 per trial (Fig. 3). Yield, weight, and count data were collected from marketable fruit harvested once or twice weekly throughout the commercial summer-plant harvest season, which differed farm-to-farm and year-to-year (Tables 1 and 2, Fig. 3). Fruit from peak and late season harvests were sampled for measuring fruit firmness, total soluble solids (TSS), and titratable acidity (TA), as previously described (Petrasch et al. 2022). We sampled four fruit per plot per harvest for fruit firmness, TSS, and TA measurements.

'UC Eclipse' and 243 to 262 other hybrids and check cultivars were screened in the field for resistance to Fusarium wilt race 1, Verticillium wilt, and Phytophthora crown rot (PhCR) using previously described artificial inoculation protocols, screening methods, and visual disease symptom ratings (Jiménez et al. 2022; Pincot et al. 2020, 2022). These experiments were conducted at the UC Davis Armstrong Plant Pathology Farm. The field sites were rotated every year and flat-fumigated with Pic-Clor 60 at a rate of 500 lb/acre ∼3 months before planting. Commercially produced bare-root plants (clones) were inoculated with individual pathogens at the time of planting as previously described (Jiménez et al. 2022; Pincot et al. 2020, 2022). Statistics were estimated from four clonal replicates per hybrid per field trial over three growing seasons (2019–20, 2020–21, and 2021–22). Hybrids were arranged in randomized complete block experimental designs. Ordinal disease scores were recorded on five dates in June and July of each year to evaluate the progression of disease symptoms and select the final time point for statistical analyses and comparisons (Table 3) (Jiménez et al. 2022; Pincot et al. 2020, 2022).

Linear mixed model (LMM) statistical analyses of traits observed within and across trials were performed using the R package *lme4* with replicates, subsamples, years, and locations as random effects and hybrids as fixed effects (Bates et al. 2015). Hybrid × trial interaction effects were included in the LMMs used for across-trial statistical analyses. Variance components were estimated using REML in the R package '*lme4*' (Bates et al. 2015). Estimated marginal means (EMMs) for hybrids within and across years and linear contrasts between 'UC Eclipse' and check hybrid EMMs were estimated using the R package '*emmeans*' (Lenth et al. 2019). Linear contrasts were used to test the null hypothesis of no significant difference between 'UC Eclipse' and check cultivar EMMSs.

Description

The photoperiod insensitivity of 'UC Eclipse', predicted by the homozygosity of *PF*-associated SNPs, was confirmed by 3 years of field testing

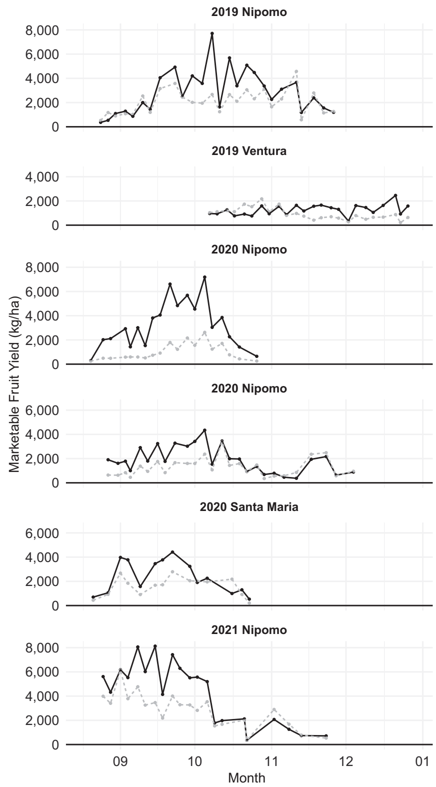

Fig. 3. Yields of marketable fruit are shown for 'UC Eclipse' (solid black lines) and the check cultivar 'Portola' (dashed gray lines) grown on California farms over three summer-plant growing seasons. The estimated marginal means (EMMs) for both cultivars are plotted for every harvest. The number of harvests per trial varied from 14 to 26. The Santa Maria 2020 trial was grown using organic production practices. The other trials were grown using conventional production practices. Trials were grown on two different Nipomo farms in 2020.

Table 3. Fusarium wilt, Verticillium wilt, and Phytophthora crown rot resistance score[i] estimated marginal means (EMMs) for 'UC Eclipse' and check cultivars observed in 2019–20, 2020–21, and 2021–22 disease resistance screening studies in Davis, CA.

Disease[ii]	Check cultivar	UC Eclipse EMM	Check cultivar EMM	t[iii]	P value[iv]
Fusarium wilt	UCD Finn	1.2	3.8	−5.32	<0.0001
	UCD Mojo		2.1	−1.81	0.08
	San Andreas		1.2	0.12	0.91
	Monterey		3.4	−4.39	<0.0001
Verticillium	UCD Finn	2.1	3.0	−1.62	0.11
	UCD Mojo		2.0	0.28	0.78
	San Andreas		1.3	1.14	0.26
	Monterey		2.4	−0.44	0.66
Phytophthora	UCD Finn	2.8	3.1	−0.41	0.69
	UCD Mojo		3.1	−0.46	0.65
	San Andreas		1.8	1.37	0.18
	Monterey		3.1	−0.37	0.71

[i] The ordinal symptom rating scales were identical for each disease: 1 = highly resistant, 2 = moderately resistant, 3 = moderately susceptible, 4 = susceptible, and 5 = highly susceptible.
[ii] The fungal pathogens causing these diseases are *Fusarium oxysporum* f. sp. *fragariae* (Fusarium wilt), *Verticillium dahliae* (Verticillium wilt), and *Phytophthora cactorum* (Phytophthora crown rot).
[iii] *t*-statistics for linear contrasts between the EMMs for 'UC Eclipse' and check cultivars.
[iv] The probability of a greater *t*-statistic by chance for the null hypothesis of no difference between EMMs for 'UC Eclipse' and check cultivars.

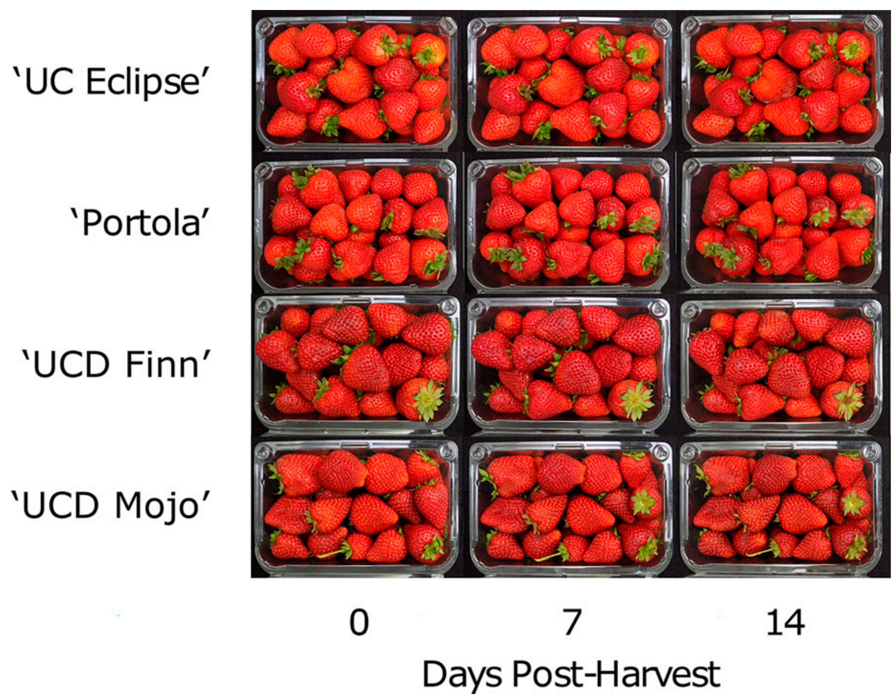

Fig. 4. 'UC Eclipse' and summer-plant check cultivar fruit stored in 454-g clamshells in the dark at 4 °C for 0, 7, and 14 d post-harvest.

in coastal California summer-plant production systems. 'UC Eclipse' consistently flowered and fruited throughout the summer-plant harvest seasons in Ventura, Nipomo, and Santa Maria, where photoperiods ranged from 9.8 to 14.5 h (Tables 1–2, Fig. 3). The production of fruit declined in the late fall months (Fig. 3).

The cumulative marketable fruit yields of 'UC Eclipse' were greater than the check cultivars in every trial (Table 1). The yield differences were statistically significant ($P \leq 0.05$) for 16 of the 18 trial × check cultivar comparisons (Table 1). Most importantly, the yields of 'UC Eclipse' were 37.2% to 223.9% greater than 'Portola', the Fusarium wilt–resistant summer-plant check cultivar (Table 1). The yields of 'UC Eclipse' exceeded 'Portola' by 25,736 kg/ha across trials, a 54% increase (Table 2). The yield difference between 'UC Eclipse' and 'Portola' (43,344 kg/ha) was particularly extreme in one of the Nipomo 2020 trials (Table 1). The reasons for this are unclear. With this outlier excluded, 'UC Eclipse' yields were estimated to be 37.2% to 49.8% greater than 'Portola' across trials.

'UC Eclipse' meets or exceeds the fruit quality and shelf life standards necessary for large-scale production and long-distance shipping of cold-stored fruit in California (Table 2, Fig. 4). 'UC Eclipse' fruit were significantly larger and firmer than 'Portola' (Table 2, Fig. 4). The TSS content for 'UC Eclipse' (7.5%) was significantly lower than 'Portola' (8.0%); however, the TSS/TA ratio for 'UC Eclipse' (10.1) was not significantly different from 'Portola' (10.1). The shelf life of 'UC Eclipse' fruit cold-stored in the dark for 14 d post-harvest was not significantly different from 'UCD Finn', 'UCD Mojo', or 'Portola' (Fig. 4). We did not observe significant time-series differences between 'UC Eclipse' and the check cultivars for fruit weight, firmness, TSS, or TA (data not shown).

The Fusarium wilt resistance of 'UC Eclipse', predicted by the heterozygosity of *FW1*-associated SNP genotypes (Pincot et al. 2018, 2022), was confirmed by 3 years of replicated testing of plants artificially inoculated with the race 1 isolate AMP132 (Table 3). The Fusarium wilt resistance score for 'UC Eclipse' ($\bar{y} = 1.2$) was not significantly different from the resistant check 'San Andreas' ($\bar{y} = 1.2$). 'UC Eclipse' was found to be moderately resistant to Verticillium wilt ($\bar{y} = 2.1$; Table 3). The strength of resistance was not significantly different from 'UCD Finn' ($\bar{y} = 3.0$; $P = 0.11$), 'UCD Mojo' ($\bar{y} = 2.0$; $P = 0.78$), or 'San Andreas' ($\bar{y} = 1.3$; $P = 0.26$). 'UC Eclipse' was found to be moderately susceptible to PhCR ($\bar{y} = 2.8$; Table 3). The strength of resistance was not significantly different from 'UCD Finn' ($\bar{y} = 3.1$; $P = 0.69$), 'UCD Mojo' ($\bar{y} = 3.1$; $P = 0.65$), or 'San Andreas' ($\bar{y} = 1.8$; $P = 0.18$).

Availability

The release of 'UC Eclipse' was approved by the College of Agricultural & Environmental Sciences at UC Davis in 2023. The US Plant Patent for 'UC Eclipse' is pending. Plant Breeder's Rights are pending in territories outside the United States. Those interested in acquiring plants of 'UC Eclipse' for commercial purposes should contact the Strawberry Licensing Program at Innovation Access in the Office of Research at UC Davis (https://itc.ucdavis.edu/strawberry-licensing-program/). Disease-free stock plants can be obtained from UC Davis Foundation Plant Services (https://fps.ucdavis.edu/strawberry.cfm).

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