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'UC Monarch', a Short-day Strawberry Cultivar with a Compact Plant Habit and Long Fruit Trusses Designed To Improve Harvest Speed and Efficiency

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Strawberries (*Fragaria ×ananassa* Duchesne) are produced in diverse climates, environments, and production systems (López-Aranda et al. 2011; Samtani et al. 2019; Yoshida 2013; Zacharaki et al. 2024). The versatility and adaptability of this plant has enabled production to expand around the globe by 1200% over the last 60 years, from 0.75 million t in 1960 to 9.57 million t in 2022 (https://www.fao.org/faostat/). Although strawberry production has been dominated by large-scale open-field production systems in optimum coastal environments (López-Aranda et al. 2011), protected- and substrate-culture production systems are continually evolving and expanding to meet global demand (Guerena and Born 2007; Samtani et al. 2019; Yoshida 2013; Zacharaki et al. 2024). Strawberry cultivars with plant architectures better adapted to those production systems similarly need to evolve. Unlike tomato (*Solanum lycopersicum*), a species in which breeding has dramatically altered plant architecture and created cultivars tailored for protected- and substrate-culture growing systems (Moraes et al. 2019; Hemming et al. 2020; Reinhardt and Kuhlemeier 2002), the strawberry cultivars being farmed indoors today have largely been developed for and migrated from open-field growing systems. The plasticity and evolvability of strawberry plant architecture remains uncertain and understudied.

Beyond the ever-expanding array of production challenges and growing systems, several billion strawberries are harvested by hand worldwide each year (López-Aranda et al. 2011; Samtani et al. 2019; Zacharaki et al. 2024). Using an average fruit weight of 28 g/fruit, we estimate that ∼46 billion strawberries were hand-harvested on California farms in 2022 (https://quickstats.nass.usda.gov/results/3A6A5C49-DC2B-3BFC-9FE1-32D938C7CBF1). Similarly, using a fruit weight range of 18 to 28 g/fruit, we estimate that 342 to 532 billion strawberries were hand-harvested worldwide in 2022 (https://www.fao.org/statistics/en). The challenge of hand harvesting that much fruit underscores the importance of creating cultivars with plant architectures that improve harvest efficiency and ergonomics and are better designed for machine harvesting systems (Chang and Huang 2024; Ge et al. 2019; Ren et al. 2024; Yu et al. 2024; Zacharaki et al. 2024).

Using our pedigree database (Pincot et al. 2021; expanded and updated Feb 2024), we estimate that at least 3149 strawberry cultivars have been introduced since 1806 to support strawberry production. There is scant information on plant architecture variation in the plant patent and historical records describing those cultivars. While the improvement of strawberry cultivars has been substantial (Feldmann et al. 2024; Whitaker et al. 2011), strawberry plant architecture has either been subtly modified or not yet been dramatically altered by breeding, and genes affecting plant architecture have not been described, apart from the *PERPETUAL FLOWERING* (*PF*) gene (Ahmadi et al. 1990; Gaston et al. 2013; Bringhurst and Voth 1980). *PF* alleles alter strawberry plant architecture by regulating photoperiod- and temperature-dependent flowering, the

Fig. 1. The short-day strawberry cultivar 'UC Monarch'. (**A–B**) The compact plant habit and long fruit truss architecture of 'UC Monarch' observed Feb 2022 (near the first harvest) in Oxnard, CA, USA. (**C**) Field testing of 'UC Monarch', check cultivars, and other hybrid individuals in Oxnard, CA, USA (Feb 2022). (**D–F**) The compact plant habit and long fruit truss architecture of 'UC Monarch' observed Apr 2023 in Santa Maria, CA, USA. (**G**) The first fruit of 'UC Monarch' observed Feb 2023 (near the first harvest) in San Quintín, Mexico. (**H**) Tabletop substrate-culture production of 'UC Monarch' in Watsonville, CA, USA (Apr 2023). (**I**) Open-field production of 'UC Monarch' in Santa Maria, CA, USA (Apr 2023). (**J–L**) 'UC Monarch' harvested Apr 2023 in Santa Maria, CA, USA. Photographs D, E, I, and J–L by Fred Greaves for UC Davis.

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Table 1. Across-environment estimated marginal means (EMMs) for cumulative marketable fruit yield and fruit quality traits for 'UC Monarch' and check cultivars grown on farms in Oxnard and Santa Maria, CA, USA, over the 2020–21 and 2021–22 growing seasons.

Trait[i]	Cultivar	EMM	t[ii]	P value[iii]
Yield (kg/ha)	UC Monarch	40,022		
	Fronteras	43,526	−0.68	0.51
	UCD Victor	45,814	−1.11	0.29
	UC Surfline	52,529	−2.43	0.03
Size (g/fruit)	UC Monarch	25.6		
	Fronteras	32.4	−4.73	0.0003
	UCD Victor	29.6	−2.72	0.02
	UC Surfline	29.5	−2.69	0.02
Firmness (g-force)	UC Monarch	307.4		
	Fronteras	225.9	3.14	0.003
	UCD Victor	296.5	0.88	0.38
	UC Surfline	339.1	−1.22	0.23
TSS (%)	UC Monarch	7.73		
	Fronteras	8.66	−3.06	0.004
	UCD Victor	7.89	−1.01	0.32
	UC Surfline	8.18	−1.5	0.14
TA (%)	UC Monarch	0.70		
	Fronteras	0.86	−4.45	<0.0001
	UCD Victor	0.76	−3.22	0.002
	UC Surfline	0.86	−4.58	<0.0001
TSS/TA	UC Monarch	11.00		
	Fronteras	10.44	0.97	0.34
	UCD Victor	10.47	1.73	0.09
	UC Surfline	9.82	−2.04	0.05

[i] Cumulative marketable fruit yields were estimated from fruit harvested on commercial schedules (once or twice weekly) over the entire short-day growing season on each farm and were corrected for farm-specific planting density differences. Fruit firmness, total soluble solids (TSS), and titratable acidity (TA) were estimated from multiple fruit/replication sampled from two harvests/trial. EMMs were estimated from fruit harvested from two 12- or 24-plant plots/entry/environment.
[ii] t statistics for linear contrasts (EMM1 – EMM2) between 'UC Monarch' and check cultivar EMMs.
[iii] The probability of a greater t statistic by chance for tests of the null hypothesis of no difference between EMMs (H_0: EMM1 = EMM2).

transition from sexual to asexual reproduction, and the timing of stolon (runner) and plantlet (daughter plant) growth (Ahmadi et al. 1990; Brukental et al. 2025; Gaston et al. 2013; Hytönen and Kurokura 2020; Prohaska et al. 2024).

Here, we describe 'UC Monarch', a short-day (*pfpf*) strawberry cultivar with a compact plant habit and long fruit trusses designed to improve fruit accessibility and harvest efficiency (Fig. 1). 'UC Monarch' was released by the College of Agriculture and Environmental Sciences at the University of California (UC), Davis in 2023 in parallel with 'UC Surfline', a short-day cultivar described in a companion paper (Knapp et al. 2025). 'UC Monarch' emerged from the early stages of our decade-long exploration of plant architecture variation and initiative to modify plant architecture through breeding. 'UC Monarch' has been extensively tested in open-field and protected-culture production systems, in addition to being selected as a prototype for robotic harvesting (Chang and Huang 2024; Ge et al. 2019; Ren et al. 2024; Yu et al. 2024). The long fruit trusses of 'UC Monarch' are designed to improve harvest speed and efficiency in open-field and protected- and substrate-culture production systems. 'UC Monarch' is resistant to Fusarium wilt, Verticillium wilt, and Phytophthora crown rot; produces high yields of large, firm, long-shelf-life fruit; and has been extensively tested on conventional and organic farms in California and Mexico.

Origin

'UC Monarch' is an individual from a full-sib family (17C138) developed by hybridizing 11C141P001 ('UCD Moxie') and 08C138P003 ('UCD Warrior'). 'UC Monarch' was internally and externally tested as 17C138P021. 'UCD Moxie' is a day-neutral (*PFpf*) cultivar released by UC Davis in 2019 (#USPP16/501,376). 'UCD Warrior' is a short-day (*pfpf*) cultivar released by UC Davis in 2019 (#USP16/501,373). The parents were manually hybridized in a glasshouse at UC Davis over Winter 2016–17. Seeds of the 17C138 family were germinated Jun 2017. Seedlings were transplanted to a glasshouse Jul 2017, hardened off in a shade house Aug 2017, and transplanted to the field Sep 2017. Clones (daughter plants) of 'UC Monarch' were propagated from a single mother plant (hybrid individual) in 2017–18. 'UC Monarch' has since been preserved by clonal propagation at Wolfskill Experiment Orchard, Winters, CA, USA. The clones produced in Winters supplied 'UC Monarch' mother plants for the propagation of bare-root plants (clones) in high-elevation nurseries in Macdoel and Dorris, CA, USA. Those bare-root plants were used for on-farm advanced testing in Oxnard and Santa Maria, CA, USA, and for disease-resistance screening in Davis, CA, USA.

'UC Monarch' was one of ∼10,000 individuals from 359 full-sib families grown at Wolfskill Experiment Orchard in 2017–18. This population was phenotyped in the spring of 2018 to identify and select individuals with a compact growth habit, long fruit trusses, and high yields of large, firm fruit. The short-day classification of 'UC Monarch' was confirmed by 4 years of field testing (2020–21 to 2023–24) on multiple farms in California and Mexico (this cultivar ceases flowering as photoperiods and temperatures increase in late spring and approach the summer solstice). 'UC Monarch' was predicted to be homozygous for a recessive *PF* allele (*pfpf*) using an Axiom

Table 2. Within-environment estimated marginal means (EMMs) for cumulative marketable fruit yield for 'UC Monarch' and check cultivars grown on farms in coastal California over the 2020–21 and 2021–22 growing seasons.[i]

Location	Season	Cultivar	EMM (kg/ha)	t[ii]	P value[iii]
Oxnard	2020–21	UC Monarch	51,440		
		Fronteras	51,837	−0.04	0.97
		UCD Victor	66,902	−1.48	0.24
		UC Surfline	71,788	−1.95	0.15
Santa Maria	2020–21	UC Monarch	51,806		
		Fronteras	60,036	−1.35	0.27
		UCD Victor	58,598	−1.12	0.35
		UC Surfline	58,554	−1.11	0.35
Oxnard	2021–22	UC Monarch	14,600		
		Fronteras	21,729	−11.56	0.001
		UCD Victor	15,479	−1.42	0.25
		UC Surfline	19,610	−8.12	0.003
Santa Maria	2021–22	UC Monarch	34,855		
		Fronteras	36,022	−0.12	0.91
		UCD Victor	28,492	0.64	0.57
		UC Surfline	54,803	−1.89	0.16

[i] Linear contrasts between estimated marginal means (EMMs) for 'UC Monarch' and check cultivars were estimated for each environment. Cumulative marketable fruit yields were estimated from fruit harvested on commercial schedules (once or twice weekly) over the entire short-day growing season on each farm and were corrected for farm-specific planting density differences. EMMs and test statistics were estimated from the phenotypes of fruit harvested from two 24-plant plots/entry.
[ii] t statistics for linear contrasts (EMM1 – EMM2) between the EMMs for 'UC Monarch' and check cultivars.
[iii] The probability of a greater t statistic by chance for tests of the null hypothesis of no difference between EMMs (H_0: EMM1 = EMM2).

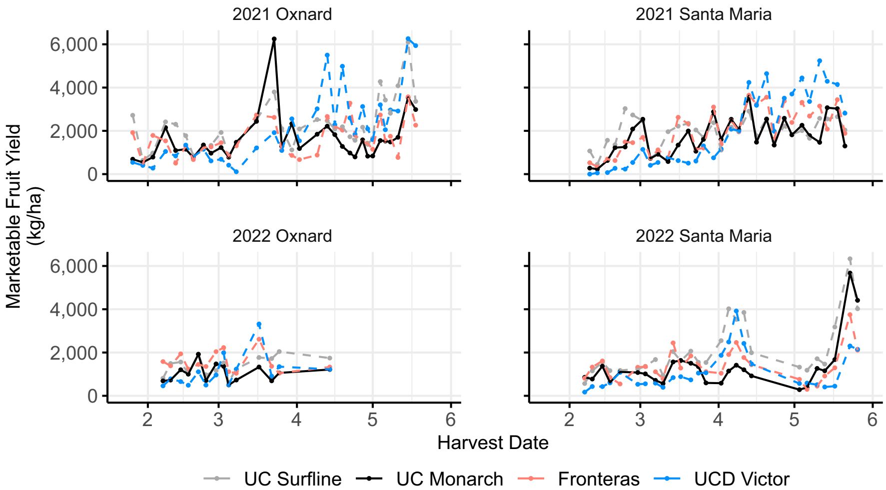

Fig. 2. Yields of marketable fruit are shown for 'UC Monarch' (solid black lines) and three check cultivars (dashed colored lines) grown on farms in Oxnard and Santa Maria, CA, USA, over the 2020–21 and 2021–22 growing seasons. The phenotypic means (estimated marginal means) for every harvest are plotted. The number of harvests ranged from 14 to 37 across environments (years × locations). Harvests were discontinued early on the Oxnard farm in 2022. Harvests on the other farms ranged from 33 to 37 and spanned the typical short-day harvest seasons in those environments. UCD = University of California, Davis.

50K array SNP marker (AX-184947290) associated with the *PF* locus (Hardigan et al. 2020).

We completed two seasons of advanced testing of 'UC Monarch', three short-day check cultivars ('Fronteras', 'UCD Victor', and 'UC Surfline'), and other short-day hybrid individuals (advanced selections) on farms in Oxnard and Santa Maria, CA, USA, to support the release of this cultivar (Tables 1 and 2; Fig. 2). The statistics reported here were estimated from full-season harvests of fruit in the 2019–20, 2020–21, and 2021–22 short-day growing seasons on those farms and from disease resistance screening studies conducted over the 2019–20, 2020–21, and 2021–22 growing seasons on the Armstrong Plant Pathology Farm at UC Davis. 'UC Monarch' has since been grown on 16 conventional and organic farms along the Pacific Coast of North America, from central western Mexico (Jalisco, Michoacan, and Guanajuato) to the south and central coasts of California (Ventura to Santa Maria). The production systems on those farms included open-field and protected-culture. 'UC Monarch' was also field tested in robotic harvesting pilot studies on farms in Oxnard and Nipomo, CA, USA, over the 2021–22 and 2022–23 growing seasons.

Clones (asexually propagated bare-root plants) for advanced testing were produced in high-elevation nurseries (Dorris, CA, USA) using standard production and propagation practices and postharvest chilling treatments optimized for the short-day market segment. Clones were harvested in September, trimmed, and directly planted in October of each year in Oxnard and Santa Maria, CA, USA. 'UC Monarch', check cultivars, and other hybrid individuals were grown in two 12-plant plots in the first year of testing and two 24-plant plots in subsequent years of testing. The plots were arranged in randomized complete blocks experiment designs. These experiments were grown using the management practices, bed configurations, plastic mulches, planting densities, planting dates, irrigation, fertilization, and pesticide application decisions and schedules, and harvest schedules of our industry cooperators. The number of harvests ranged from 14 to 33 in each yield trial (Fig. 2). Marketable fruit yield, count, and weight were recorded at each harvest. We collected and analyzed 2472 observations for these traits to support statistical analyzes and selection decisions. We sampled fruit from early and peak season harvests to phenotype hybrids for firmness, total soluble solids (Brix), and titratable acidity. Over three growing seasons, 2449 observations were collected for these traits to support statistical analyzes and selection decisions.

'UC Monarch', check cultivars, and 230 to 262 other hybrid individuals (full-sib progeny) were phenotyped for resistance to Fusarium wilt, Verticillium wilt, and Phytophthora crown rot over three growing seasons at Armstrong Farm, Davis, CA, USA. Hybrids were screened using bare-root plants (four clones/hybrid) that were artificially inoculated with a single pathogen, planted in fumigated ground and isolated, disease-specific blocks in November, and phenotyped for disease symptoms in late spring and early summer using established protocols and ordinal disease symptom ratings (Jiménez et al. 2023; Knapp et al. 2024; Pincot et al. 2020, 2022). We collected and analyzed 31,404 observations for these traits to support statistical analyzes and selection decisions.

Table 3. Across-year estimated marginal means (EMMs) for Fusarium wilt, Verticillium wilt, and Phytophthora crown rot resistance scores[i] for 'UC Monarch' and check cultivars observed in 2019–20, 2020–21, and 2021–22 disease resistance screening trials at Armstrong Farm, Davis, CA.

Disease[ii]	Cultivar	EMM	t[iii]	P value[iv]
Fusarium wilt	UC Monarch	1.22		
	Fronteras	1.09	0.30	0.77
	UCD Victor	1.09	0.31	0.75
	UC Surfline	1.02	0.47	0.64
	UCD Warrior	1.47	−0.55	0.59
	San Andreas	1.15	0.12	0.9
Verticillium wilt	UC Monarch	1.79		
	Fronteras	1.71	0.18	0.86
	UCD Victor	2.3	−1.08	0.29
	UC Surfline	1.62	0.39	0.70
	UCD Warrior	2.56	−1.65	0.10
	San Andreas	1.29	0.72	0.47
Phytophthora crown rot	UC Monarch	2.04		
	Fronteras	2.54	−0.90	0.37
	UCD Victor	2.19	−0.27	0.79
	UC Surfline	1.67	0.66	0.51
	UCD Warrior	2.03	0.02	0.99
	San Andreas	1.83	0.28	0.78

[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 (EMM1 – EMM2) between the EMMs for 'UC Monarch' and check cultivars.

[iv] The probability of a greater t-statistic by chance for tests of the null hypothesis of no difference between EMMs (H_0: EMM1 = EMM2).

Description

The marketable fruit yields of 'UC Monarch' are competitive with the highest-yielding short-day cultivars grown in California (Tables 1 and 2; Fig. 2). The cumulative (full-season) yield of 'UC Monarch' was not significantly different from 'Fronteras' or 'UCD Victor' but was significantly lower (P = 0.03) than 'UC Surfline' across locations and years (Table 1). The yield for 'UC Monarch' was significantly lower than 'Fronteras' in one trial (Oxnard 2021–22) but not in the other years and locations and not across years and locations (Table 1). The Oxnard

2021–22 trial was atypical because adverse weather shortened the harvest season (Fig. 2).

'UC Monarch' fruit were smaller ($\bar{y}$ = 25.6 g/fruit) than those of the other check cultivars across years and locations (*P* values ranged from 0.02 to 0.003) but still above the weight (g/fruit) required for large-scale production in California. 'UC Monarch' fruit were significantly firmer than 'Fronteras' and not significantly different from the other two check cultivars (Table 1). Importantly, the firmness of 'UC Monarch' fruit persists throughout the season, whereas the firmness of 'Fronteras' decreases. The ratio of total soluble solids to titratable acidity (a perceived 'sweetness' metric) was significantly greater for 'UC Monarch' than 'UC Surfline' and not significantly different from 'Fronteras' or 'UCD Victor' (Table 1). The titratable acidity was significantly lower for 'UC Monarch' than the three check cultivars, which improved the perceived sweetness of this cultivar.

'UC Monarch' and check cultivars were confirmed to be highly resistant to Fusarium wilt race 1 (Table 3), a devastating disease widely found in California (Henry et al. 2017; Koike et al. 2009). Using a 50K Axiom array single nucleotide polymorphism (SNP) marker (AX-184226354) associated with the *FW1* locus, 'UC Monarch' was predicted to be heterozygous for *FW1*, a dominant gene that confers resistance to race 1 isolates of *Fusarium oxysporum* f. sp. *fragariae* (Hardigan et al. 2020; Pincot et al. 2018, 2022).

Similar to 'UC Surfline' (Knapp et al. 2025), 'UC Monarch is highly resistant to Verticillium wilt and Phytophthora crown rot (Table 3). The Verticillium wilt and Phytophthora crown rot resistance scores for 'UC Monarch' were not significantly different from the check cultivars: 'Fronteras', 'UCD Victor', 'UC Surfline', 'UCD Warrior', and 'San Andreas' (Table 3). Using a SNP (AX-184109190) marker associated with *RPc2*, a large-effect quantitative trait locus for resistance to Phytophthora crown rot (Jiménez et al. 2023; Mangandi et al. 2017), 'UC Monarch' was confirmed to be homozygous for the favorable *RPc2*-associated allele (Jiménez et al. 2023; Mangandi et al. 2017). The AX-184109190 SNP was genotyped using a 50K Axiom SNP array (Hardigan et al. 2020).

Availability

The release of 'UC Monarch' was approved by the College of Agricultural and Environmental Sciences at the University of California, Davis in 2023. The US plant patent for 'UC Monarch' is pending. Plant Breeder's Rights are pending in territories outside the US. Those interested in acquiring plants of 'UC Monarch' for commercial purposes should contact the Strawberry Licensing Program at Technology Transfer in the Office of Research at the University of California, Davis (https://research.ucdavis.edu/technology-transfer/plant-variety-licensing-program/strawberry-licensing-program/).

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