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The California Strawberry Industry: Current Trends and Future Prospects

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ABSTRACT

Fruit production, plant production, genetics, technological advancements, food safety practices, and dedication to sustainable practices make California the most important strawberry production area in the world. California grew 16,303 hectares of strawberries in 2023 in three growing districts located along California's Central Coast: Oxnard, Santa Maria and Watsonville-Salinas. Transplants are grown on approximately 1,627 ha at high and low elevation nurseries located up to a thousand km from fruit growing districts. Almost all fruit production is in open fields with a small amount under high plastic tunnels either in soil or on tabletops. Nursery production is almost all in open fields. In 2022, there were 13 public cultivars grown with the most popular being Monterey, Portola, Fronteras, Cabrillo, and San Andreas grown on 27%, 13%, 11%, 4% and 2% of the planted acres, respectively. All proprietary cultivars combined made up 39% of the planted acres. Fresh market makes up 81% of the harvested fruit with 19% destined for processing into concentrates, individually quick frozen, purees and juice. Most fruit are sold domestically (87%) while 13% is exported, the majority to Canada (62%) and Mexico (25%). The most important diseases are Macrophomina root rot, Fusarium wilt, Verticillium wilt, Phytophthora root rot, Botrytis fruit rot and powdery mildew. The most important arthropod pests are twospotted spider mite and Lygus bug. Current challenges include increased regulation on water quality, fumigants, pesticides, labor and increased urbanization.

KEYWORDS
Fragaria × *ananassa*; pest management; disease management; production practices; automation; cultivar; nursery production

Introduction

California is the largest producer of strawberries in the United States and the 4th largest producer in the world. It is also a major producer of strawberry plants which are sold both domestically and internationally. California's coastline and mountain valleys provide nearly ideal conditions for strawberry growth and development. The University of California Davis strawberry breeding program is in its 4th generation of breeders which have produced many of the top cultivars grown worldwide. This paper is a summary of California's unique position as a major strawberry producer in the world, the agronomic practices currently in use and current and future challenges. Integrated Pest Management for Strawberries (Strand, 2008) remains a relevant reference on California's strawberry industry and the reader is referred to that publication for a more comprehensive account. Strawberry Work Group (2021) contains more details regarding pests and growing practices and their timing within a typical season. The Strawberry Production Manual (2015) is an excellent guide to California growing practices with many useful photos.

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Climate & Geography

California's strawberry fruit production is concentrated along its central coastline between San Francisco and Los Angeles. Strawberry acreage south of Los Angeles was much larger in the 20th century but has almost disappeared due to urbanization (Strand, 2008).

Environmental conditions along California's coastline are ideal for strawberry production (Strand, 2008). Along the western side of the Coast Range mountains, California's climate is dominated by the Pacific Ocean. A semi-permanent, high-pressure area of the North Pacific Ocean moves northward during summer and southward during winter. This pattern creates a climate of warm winters, cool summers, small daily and seasonal temperature ranges, and high relative humidity. The temperature of ocean water reaching the surface from deeper levels varies from about 9.4°C in winter to 12.8°C in late summer along the northern California coast, and from 13.9°C – 18.3°C on the Southern California coast. As prevailing winds move air eastward across the Pacific Ocean toward California's coastline, it picks up moisture. This moist air passes over the cooler waters along the coastline, often condensing into a marine layer which keeps temperatures low and humidity high along a narrow band of coastline where strawberries are grown.

In contrast to strawberry fruit production, plant production occurs at high- and low-elevation nurseries. The elevation and associated temperatures allow for accumulation of chilling hours necessary for successful use as transplants (150 – 400 hours below 7.2°C) prior to digging/harvest (Strand, 2008). Low elevation nurseries are located in California's central valley (152 m elevation) while high elevation nurseries are located near the Oregon-California border at an elevation of 1,295 m (Figure 1).

Acreage and Value

In 2023, California grew 16,303 ha of strawberries (FAO, 2023). This is close to the highest hectarage ever grown which occurred in 2013 (16,518 ha). This hectarage resulted in a total yield (fresh + processed) of 1,081,817,234 kg fruit and a yield of 66,355 kg fruit per hectare (Figure 2) (FAO, 2023). In the US, California makes up 85 – 90% of strawberry production with most of the remaining 10 – 15% produced in the state of Florida. There is concern that per-acre yields have decreased since 2018. There are many possible explanations for this, some market driven (e.g., terminating crops early due to poor market prices) and others of a biological nature (e.g., increased pest pressures, cultivar performance, weather events and loss of effective fumigants).

Globally in 2021, US strawberry acreage ranked 4th at 19,983 ha behind China (318,744 ha), Russian Federation (35,451 ha) and Poland (33,886 ha). US fruit production ranks 2nd at 1,211,090 tonnes, behind China at 3,389,620 tonnes. According to FAO, US production per unit area ranks first in the world at 60,579 kg/ha (Table 1) (FAO, 2023).

Plant Production (Nurseries)

In addition to producing 85 – 90% of the fruit in the US, California has a large strawberry nursery industry that produces over 1.5 billion plants annually. In 2022, there were 1,627 ha of strawberry nurseries with 1,295 ha (80%) at high elevation (1295 m) and 324 ha (20%) at low elevation (near sea level) (Smith, 2022). Both high and low elevation nurseries are separated from fruit production fields by mountain ranges and up to 1,000 km.

These two distinct production regions provide climatic requirements necessary for specific markets. Low elevation nurseries are located near Turlock and Manteca, in California's central valley. Most of the production at low elevation nurseries (~70%) is used for summer planting in California and for international production, while the remainder is used for plant increase at high elevation nurseries. Climatic conditions at low elevation nurseries allow for planting in late May through early June and harvesting in late December through January. Plants harvested at low elevation nurseries are placed in long-term cold storage at −2.2°C for planting at high elevation nurseries in April of the same year or for summer planting in Oxnard and Santa Maria in June and July. Plants placed in long-term cold storage are referred to as "frigo" plants.

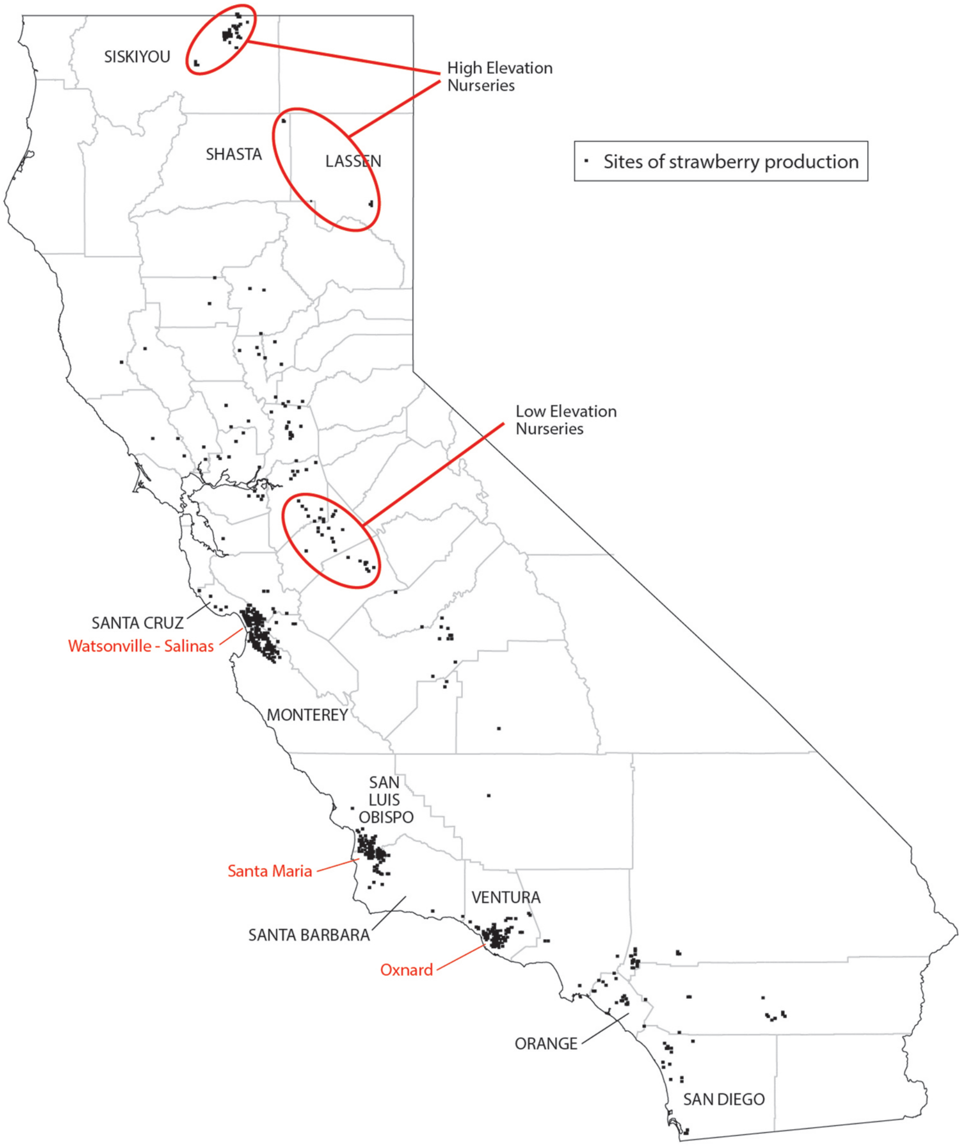

Figure 1. Map of strawberry fruit production districts and plant production areas (nurseries). Cartography by Bill Nelson.

Plant production at high elevation allows for sufficient chilling of plants in time for harvest. Chilling hours between 150 and 400 hours is desirable for optimum plant vigor and fruit production (Strand, 2008). Insufficient chilling results in low vigor plants while excessive chilling results in excessive vegetative growth. Both extremes result in plants that produce lower yields. Supplemental chilling in refrigerated rooms provides a means of adding chilling hours post-harvest and pre-planting. Of the plants produced at high elevation nurseries, 80% are produced near Macdoel and the remainder in Susanville, McArthur and south-central Oregon. Approximately 85% of the plants produced are sold in California and northern Baja California, Mexico while 10% is exported to Florida and 5% to Central Mexico. California also supplies mother stock to Canada for their nurseries and to Mexico for its plug plant nurseries. Most of the world is dependent upon the California mother and foundation stock for their strawberry industries.

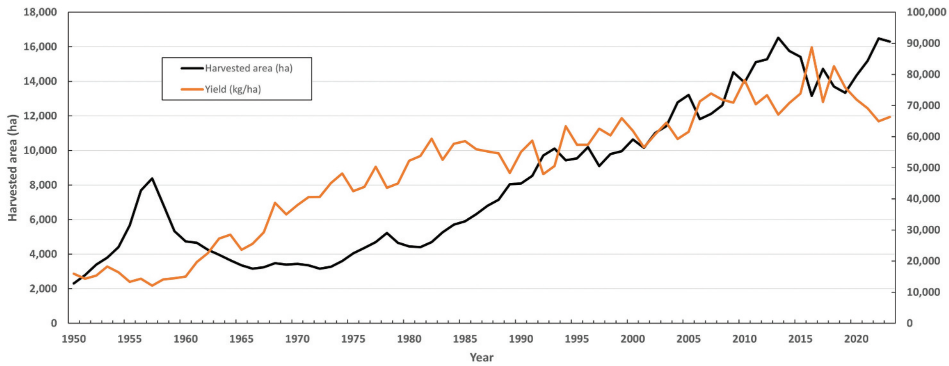

Figure 2. California strawberry fruit producing hectarage and yield per hectare from 1950 – 2022.

Table 1. Top 10 strawberry producing countries in the world in 2021, sorted in descending order according to production per unit area, total production and harvested area.

Country	Production (hg/ha)	Country	Total production (tonnes)	Country	Harvested area (ha)
U.S.A.	605,787	China	3,389,620	China	129,046
Netherlands	557,338	U.S.A.	1,211,090	Russian Fed.	35,466
Morocco	502,941	Türkiye	669,195	Poland	33,900
Spain	499,404	Mexico	542,891	U.S.A.	19,992
Albania	478,537	Egypt	470,913	Türkiye	18,676
Israel	478,106	Spain	360,570	Egypt	12,579
Mexico	456,016	Russian Fed.	237,200	Germany	12,500
Kuwait	452,200	Brazil	197,000	Mexico	11,905
Greece	400,791	Rep. of Korea	193,852	Belarus	9,510
Brazil	387,506	Poland	162,900	Ukraine	8,000

Source: www.fao.org/faostat.

Plant Production Practices

The production system for nurseries is dramatically different from fruit production fields. Although plant production practices will vary according to each grower, there are some common agronomic practices. One of the common planting systems includes bareroot plants, commonly referred to as "mother plants" from long-term cold storage (−2.2°C) being transplanted into flat field soil (no beds) in one or two lines of plants spaced 36 cm between plant lines and 30 – 46 cm between plants within a line. A large space (2 m) is left between lines of mother plants to allow for eventual colonization by stolons/runners and daughter plants. Drip irrigation tape is added to the unplanted area between mother plants as the season progresses and mother plants begin to produce stolons and daughter plants (Figure 3).

At high elevation nurseries, some growers cover mother plants with low plastic tunnels or ground cloth which are removed as temperatures rise and plants produce stolons. The recent introduction of low plastic tunnels combined with drip irrigation provides a warmer environment for plants early in the season, improving stand establishment and yields while eliminating overhead irrigation. Like all innovations, this practice will likely be adopted by more growers if the benefits outweigh the costs. This planting scheme will use 32,000 – 42,000 mother plants per hectare to establish the field and produce approximately 951,000 plants/ha. Planting density is determined by the genetic capacity of each cultivar to produce daughter plants. Poor stolon production is a desirable trait for fruit growers but undesirable for plant producers. Thus, a balance must be struck for stolon production that is optimized for both fruit and plant producers. Any cultivar not producing at least 741,000 daughter plants per hectare is not likely to be grown (D. Thomas and M. Nelson, *personal communication*).

Figure 3. Nursery growing practices. Low plastic tunnels (left) and daughter plant production in space between mother plants (right).

Fruit Production

In 2023, California produced 1,081,817,234 kg of fruit on 16,304 ha (California Strawberry Commission). Fruit production is concentrated in four districts located along central and southern California's coastline. Beginning with the southernmost district (Orange County, San Diego County and Coachella) strawberries were grown on 89 ha, making up only 0.7% of the state's strawberry acreage. This district was once the most concentrated area for strawberry production in the state but has nearly disappeared due to urbanization. To the north is the Oxnard district which grew 2,549 ha of fall-planted (planting in September – November) and 1,660 ha of summer-planted (planting in May – July) strawberries. North of Oxnard is the Santa Maria district, which is now the largest production region in the state, making up 42% of the total state acreage with 4,260 ha fall-planted and 2,542 ha summer-planted acres in 2023. The northern-most district is Watsonville/Salinas with 5,194 ha of fall-planted strawberries (California Strawberry Commission). Watsonville-Salinas does not typically have any summer-planted acreage but occasionally has 4 – 8 ha.

Approximately 70% of the state's acreage is fall-planted and 30% is summer-planted. Summer planted acreage has been increasing over the last 13 years (Figure 4) as a means of increasing fruit production in the southern districts and to capitalize on higher prices during the fall and winter months. Only extreme day neutral cultivars are used for summer plantings (e.g., "Portola") since these must be able to produce fruit after planting during relatively high temperatures and long day length and continue producing fruit as daylength shortens during fall and winter months.

The dynamics of the volume of strawberries produced during the annual California production cycle is shown in Figure 5. Production begins in the south and moves northward as the season progresses. Peak yields for the entire state occur from early May – mid-June. Although yields never drop to zero, the lowest production occurs from mid-December to mid-February.

Cultural Systems

There are many elements of California strawberry production that are common to all production districts. However, each district, because of its latitude, has advantages that are optimized to meet specific market windows. For example, all the districts south of Watsonville-Salinas grow on 1.6 m wide beds with four lines of plants per bed (Strawberry Work Group, 2021). This cultural system allows for up to 64,250 plants per hectare, emphasizing higher yields early in the season when market prices are generally higher. This early-season higher yield is a tradeoff between optimal plant spacing for season-long production and tighter spacing for increased yield while plants are relatively small. In Watsonville-Salinas, the strategy emphasizes a longer season which produces higher yields per acre. For this reason, a 1.3 m bed with two lines of plants per bed are generally used. The planting density under this system is approximately 39,500 plants per hectare. While this plant density will not produce the early season yields of the 1.6 m bed system, the per-hectare yields are the highest in the state because the season is longer (Figure 6).

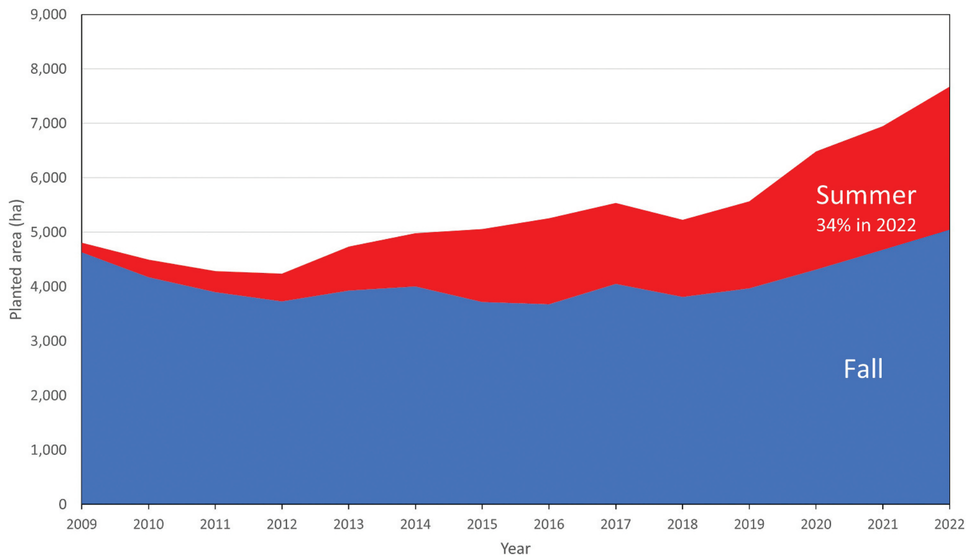

Figure 4. Stacked line chart showing the change in the proportion of fall- and summer-planted strawberries in the Santa Maria district from 2009 – 2022.

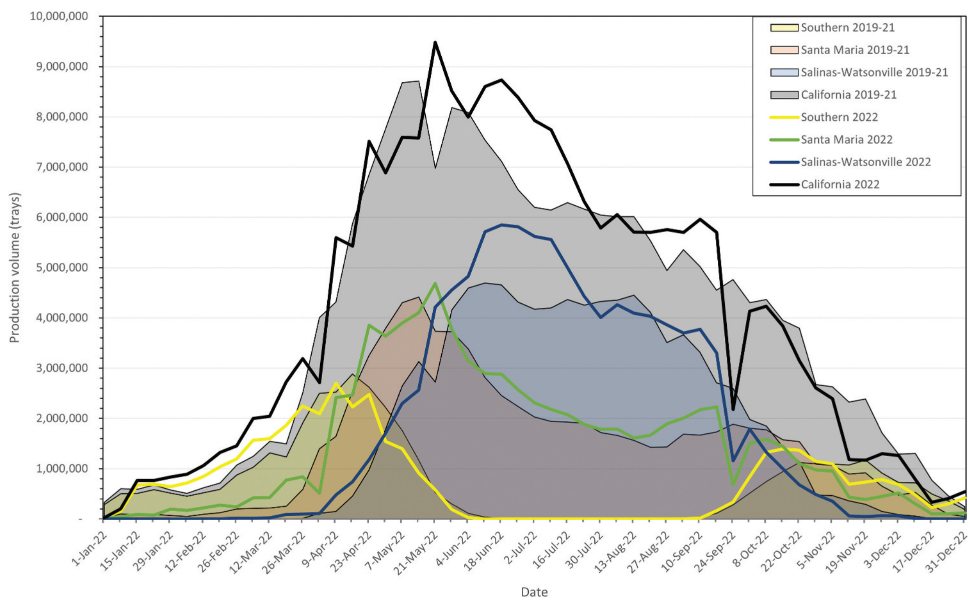

Figure 5. California strawberry production volume by district and time of year. Filled areas are the three-year average while lines show the current year (2022). Production volume is shown in "trays" which weigh 4 kg. Peak yield from fall plantings occurs in April (Southern district/Oxnard) and May (Santa Maria) while peak yield for summer plantings occurs in September-October (Santa Maria) and October-November (Southern distict/Oxnard). (Source: www.calstrawberry.com).

Nearly all California fruit production occurs on raised beds covered with plastic film. Plastic films vary in color, thickness, finish (matte or glossy) and other properties. The most common plastic mulch used in California strawberries is clear on top and black on the sides (Figure 6 left), commonly referred to as "zebra" or "skunk" plastic mulch. The clear top provides early heat transfer to the soil while the black sides provide excellent weed control. Summer plantings use white/black plastic (Figure 7 left)

Figure 6. The two bed configurations used in California: four lines of plants on 64-inch beds (1.6 m) covered in zebra plastic (left) used in Oxnard and Santa Maria; 2 lines of plants on 52-inch beds (1.3 m) covered in gray plastic (right) used in Watsonville-Salinas.

which is white on the upper side to be cooler during summer months and black on the underside to block sunlight for weed control (Table 2).

Bareroot transplants are used throughout California. These are hand-planted and usually irrigated using overhead sprinklers for stand establishment during the first month after planting. Thereafter, the crop is irrigated and fertigated through drip irrigation tape buried shallow (2 – 3 cm) and placed between or adjacent to plant lines. In the four-row system, either two or three drip lines are used. In the two-row system in Watsonville-Salinas, usually two lines of drip tape are used per bed.

While the vast majority of production is in open fields, two other production systems are used: high plastic tunnels and tabletops. High plastic tunnels use the same production system as the open fields except that plastic tunnels are used to provide protection from rain, wind and direct sunlight (Figure 7, left). Tabletop production (Figure 7, right) is practiced on a more limited scale (~200 hectares statewide). Tabletop production is done in high plastic tunnels in raised gutters. In addition to protecting fruit from rain damage, the raised gutters allow for picking in an upright position and using a soilless substrate such as coconut fiber allows for production in areas with poor soil quality while eliminating soilborne pathogens (Hernandez-Martinez et al., 2023). The tabletop system requires precision irrigation and water filtration systems which add more cost and require more maintenance. These systems also produce leachate and there is no consensus on how to treat this water. While this production system is efficient and can produce excellent fruit quality and quantity, the extra expenses associated with the infrastructure of the system make it currently less economically viable in California.

California produces more organic strawberries than any other area of the world. In 2023, 2,140 ha of organic strawberries were grown. This makes up 13% of the state's hectarage and has been slowly increasing since 2001 when organic hectarage began to be recorded (Figure 8). Organic hectarage may

Table 2. Plastic mulch types and purposes, listed in descending order of popularity.

Color	Heat transference[c]	Weed control	Districts with highest use
Zebra/ Skunk[b]	High	Poor on Top of Bed, Excellent on the Shoulders (Not Ssed in Organic Production)	Oxnard and Santa Maria
Green	High	Fair to Poor (Not Used in Organic)	Santa Maria and Watsonville
Brown	Moderate	Good	Oxnard and Santa Maria
White/ Black[a]	Very Low	Excellent	Oxnard and Santa Maria (summer planting)
Black	Moderate	Excellent	Oxnard, Santa Maria and Watsonville
Silver/ Black[a]	Very Low	Excellent	Watsonville

[a]Ability of plastic to transfer heat to soil and increase plant growth.
[b]Clear in the middle, black on the shoulders.
[c]Color of upper side/color of lower side.

Figure 7. High plastic tunnels is a production system used in a limited number of acres to protect the fruit from rain and direct sunlight (left). Tabletop production (right) utilizes soilless growing medium in raised troughs for upright posture during harvest and elimination of soilborne pathogens.

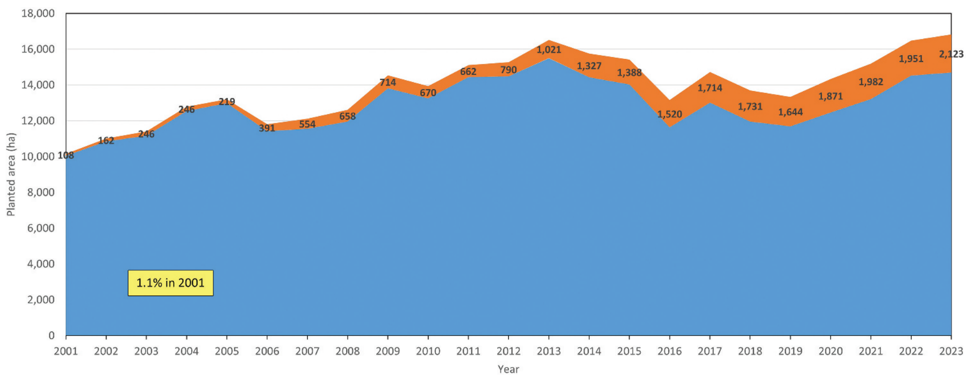

Figure 8. Stacked line chart showing the proportions of organic and conventional strawberry acreage during the period when organic acreage was tracked (2001 – 2023).

continue to increase as long as growers receive a premium price to offset the lower average yields and increased costs of organic production while managing to include sufficient crop rotation to prevent buildup of soilborne pathogens.

Many different cultivars have been grown over the last 30 years, including those from private breeding programs as well as the public breeding program at the University of California, Davis. Data on planted acreage is only available for public cultivars (www.calstrawberry.com). A bar race chart was constructed showing the acreage planted for public cultivars between 1993 and 2023 (https://www.youtube.com/watch?v=Jxu-S5VIo04). During this period, Camarosa was the most planted cultivar in California (45,428 ha) with Albion (39,479 ha) second. Camarosa stopped being grown in 2013 and Albion was grown on only 0.1% of the land (16 ha) in 2023. Monterey is currently the most popular cultivar grown in California occupying 26.6% of the planted hectarage in 2023 (Figure 9) followed by Portola (12.8%), Fronteras (10.7%), Cabrillo (4.3%) and San Andreas (1.9%). Portola is the predominant summer-planted cultivar. In the next year or two, Monterey will become the most popular cultivar ever grown in California. It is a day neutral cultivar known for its excellent flavor, color and texture as well as consistently high yields under a wide variety of environmental conditions. The high turnover in cultivars might be explained by the shifting objectives of California growers in a highly competitive environment with laws and regulations – and their effect on pests and diseases – that change the parameters under which these cultivars must perform. Certainly, the dynamics in cultivar availability and selection indicates the existence of very vigorous breeding programs interacting with innovative growers who are always searching for ways to improve their operations.

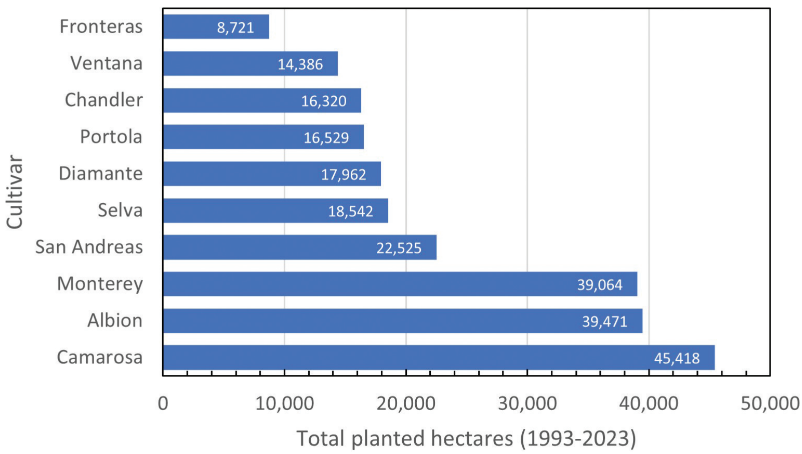

Figure 9. Top 10 most popular public cultivars grown in California between 1993 and 2023 as measured by total planted area over time.

Harvesting

Currently, strawberries are hand-harvested and packed into clamshells in the field (Figure 10). Several harvest aids are in use to improve labor efficiency. These are machines that travel through the field, in front of harvest workers, and reduce the distance and time it takes to palletize trays/boxes of clamshells and remove them from the field. The Harvest Pro (Figure 11, right) spans 7 – 11 beds with conveyor belts that bring trays of clamshells to a central platform where fruit quality control and palletization occurs. Another version of a harvest aid is the "mercado" (Figure 11, left) which is self-guided using a "tongue" that rests in the furrow and guides its movement forward (Figure 11, left: insert). The mercado travels in front of five pickers according to the speed controlled by the pickers. Trays of fruit are removed at the ends of the beds and palletized separately.

Figure 10. Hand harvesting strawberries into 1-lb (454 g) plastic clamshells placed in fiberboard trays.

Figure 11. Harvesting aids "mercado" (left) and furrow-guided tongue (insert) and "Harvest Pro" (right) improve labor efficiency by reducing the time required to transfer and palletize boxes at the edge of the field.

Figure 12. Advanced Farm's robotic harvester doing field-scale harvesting.

Over the last decade, robotic harvesting was under development by several commercial engineering firms. These include CROO Robotics (https://www.harvestcroorobotics.com/), Agrobot (https://www.agrobot.com/), Tortuga (https://www.tortugaagtech.com/) and Advanced Farm (https://advanced.farm/) (Figure 12). Several firms have developed machines that can harvest fruit under field conditions, but there are no examples of adoption of robotic harvesting except for a small-scale, trial basis. Some of the obstacles to success are fruit visibility (especially in large plants), damage to fruit during picking, speed, the need for additional crews to harvest fruit missed by robots, and a separate step for packing the harvested fruit into clamshells (Xiong et al., 2019). Because of the difficulty in finding fruit on large plants, robotic harvesting has focused on the early season when plants are smaller and fruit are fewer and larger. While great progress has been made, it remains uncertain if robotic harvesting will become a reality in California strawberry production.

In addition to robotic harvesting, other automation efforts have focused on optimized bug vacuuming (removal of Lygus bugs by use of tractor-mounted vacuums) (Figure 13), calyx removal during processing (decapping), runner/stolon cutting, high tunnel arch removal and transplant hole punching.

Figure 13. A recently optimized tractor-mounted bug vacuum improved the efficacy of removing Lygus bugs by 2.2 times over the previous version (Wells et al., 2020).

Processing

The two main markets for California strawberries are fresh and processing. Fresh market is the goal for all fruit grown in California since it commands the highest price. When the quality parameters (e.g., shape, color, ripeness) for fresh market cannot be met, fruit can be sold to a processing facility. In 2023 there were 13 strawberry processing facilities in California which process strawberries into (in order of value by weight) concentrates, individually quick frozen (IQF), purees and juice. The proportion of harvested fruit sold as fresh vs. processed for the last seven years (2017–2023) was 19% processed and 81% fresh with an average price of $1.20/kg USD for the processed fruit. For comparison, the average annual market price for fresh market strawberries for the same years was $2.76/kg USD (www.calstrawberry.com).

Export Markets

California strawberries are exported to over 30 countries. In 2022, 945,704,704 kg were produced with 274,904,573 kg (13.2%) exported. Canada and Mexico are the largest importers of California strawberries, importing 62.3% and 24.9%, respectively, of the total exports by weight. The remaining destinations for exported fruit include Japan (2.9%), Saudi Arabia (2.1%), United Emirates (2.1%), Hong Kong (0.8%), Kuwait (0.8%), South Korea (0.8%), and the United Kingdom (0.1%) (Table 3) (www.calstrawberry.com).

Pests and Diseases

The most significant arthropod pests of strawberry in California are Lygus bug (*Lygus hesperus*), twospotted spider mites (*Tetranychus urticae*) and spotted wing Drosophila (*Drosophila suzukii*) (Strawberry Work Group, 2021; Lahiri et al., 2022). Other arthropod pests of concern are Lewis mite, cyclamen mite, whitefly, aphid, thrips and cutworms.

A common, non-chemical method of managing Lygus bug in California is the use of bug vacuums (Figure 13) which suck up Lygus bugs from the canopy and impale them against fan blades and

Table 3. Top 10 destinations for strawberries exported from California in 2022.

Country	Weight (kg)	%	Value ($USD)
Canada	74,114,314	62.3%	271,792,906
Mexico	29,580,366	24.9%	73,205,816
Other	4,878,030	4.1%	22,670,932
Japan	3,494,136	2.9%	28,368,147
Saudi Arabia	2,529,845	2.1%	20,390,009
United Arab Emirates	1,457,856	1.2%	10,416,187
Hong Kong	1,006,319	0.8%	9,719,732
Kuwait	935,037	0.8%	6,249,929
Korea, South	911,986	0.8%	3,185,104
United Kingdom	101,485	0.1%	353,388
Total	**119,009,374**	**100.0%**	**446,352,150**

Source: https://calstrawberry.org.

perforated baffles. Recent improvements to bug vacuum design has resulted in 2.2 times greater efficiency (Wells et al., 2020). This method is supplemented using effective insecticides to achieve adequate control.

Twospotted spider mites are managed using predatory mites and miticides. Predatory mites are *Phytoseiulus persimilis* and *Neoseiulus californicus*, each with its own specific requirements for optimal growth and development. When using miticides, a balance must be struck between optimum efficacy against the target pest (twospotted spider mite) and non-target predatory mites as well as application timing. Miticide and insecticide resistance has been documented and is compromising the efficacy of these products (Jensen, 2023).

The most significant root diseases are Macrophomina root rot (caused by *Macrophomina phaseolina*), Fusarium wilt (caused by *Fusarium oxysporum* f. sp. *fragariae*), Verticillium wilt (caused by *Verticillium dahliae*) and Phytophthora root rot (caused primarily by *Phytophthora cactorum*) (Holmes, 2020). Recent disease surveys show that the prevalence of these diseases varies by district with the highest incidence of Macrophomina root rot in areas furthest south and furthest from the coast (Steele et al., 2023). Phytophthora root rot was least prevalent, especially in the Oxnard district. Fusarium wilt was most prevalent in the Oxnard district (Steele et al., 2023, 2024). A new race of Fusarium wilt (race 2) was recently discovered that overcomes the single-gene resistance present in many current cultivars. Its presence is currently believed to be restricted to a few fields in the Oxnard district (Dilla-Ermita et al., 2023).

The most economically important diseases of fruit are Botrytis fruit rot and Rhizopus rot (leak). The most important foliar disease is powdery mildew with angular leaf spot and Zythia leaf blotch of lesser importance. Anthracnose (caused by *Colletotrichum fragariae*) can be a severe problem in some years when conditions are conducive, and the disease was established during plant production. The new virulent strain of *Neopestalotiopsis* that recently emerged in Florida (Baggio et al., 2021) has not been found in California.

There are 13 described viruses on strawberry, but these are rarely present in combinations that are economically destructive to the crop (Martin and Tzanetakis, 2006). Pallidosis is the only virus disease of economic importance that has occurred in the last 15 years. Historical observations reveal that virus diseases are cyclical and occur when whitefly populations are high. These were not controllable until the advent of neonicotinoid insecticides (e.g., imidacloprid) which California is losing due to increased regulation. Root knot nematode is only rarely present and not economically important at this time but is expected to become more important with the decreased use or elimination of soil fumigants (Steele et al., 2024).

Soilborne pathogens are managed primarily by preplant soil fumigation with chloropicrin, 1,3-dichloropropene, methyldithiocarbamates (Vapam and K-Pam) and mixtures of these. This should be combined with the use of disease resistant cultivars and crop rotation. Effective single-gene resistance to Fusarium wilt race 1 exists in many cultivars (Pincot et al., 2022). Recent work 2024 shows that dramatic gains in resistance to Macrophomina root rot was achieved through transgressive segregation and selection under heat and drought stress (Knapp et al., 2024 Nelson et al., 2021). Similar gains in multi-genic resistance to Verticillium wilt (Shaw et al., 2010) and Phytophthora root rot (Marin et al., 2023; Shaw et al., 2008) have been achieved. However, in practice, the only host plant resistance that is highly effective is resistance to Fusarium wilt race 1. Host plant resistance to the other root diseases (i.e., Macrophomina root rot, Verticillium wilt and Phytophthora root rot) is only a partial solution and must be combined with other practices to successfully manage these diseases. Over 50 drip-applied products have been evaluated for control of Macrophomina root rot and Verticillium wilt and none were found to be effective (Blauer and Holmes, 2023c; Holmes et al., 2020). Topical application of well-timed fungicide sprays is the main method of managing Botrytis fruit rot (Blauer and Holmes, 2023a) and powdery mildew (Blauer and Holmes, 2023b). Host resistance to powdery mildew is available in many cultivars and while it is generally not an important criterion in cultivar selection, it can be a significant deterrent to cultivar adoption by growers (e.g., “Monterey”) (Nelson et al., 1996; Palmer and Holmes, 2022). Fungicide resistance in *Botrytis cinerea* and *Podosphaera aphanis* has compromised the efficacy of many fungicides (Cosseboom et al., 2019; Palmer and Holmes, 2021).

Other concerns

California’s strawberry industry faces several important challenges. Urbanization has largely eliminated the industry in Southern California. All pesticide use is under increased regulation. Preplant soil fumigation for fruit production with methyl bromide was banned in 2016 and the remaining fumigants are under increased regulation (e.g., chloropicrin, 1,3-D, Vapam and K-Pam). This was followed by the emergence of Macrophomina root rot and Fusarium wilt as new threats to production. There is also increased regulation of irrigation water use and ground water quality. Strawberries are efficient users of irrigation water due to the advent of drip irrigation many years ago. Increased water use efficiency is now achieved through the use of drip irrigation or micro-sprinklers during stand establishment instead of solid-set overhead sprinklers (Cahn et al., 2014). Furthermore, improved bed mulch hole punches are being developed to improve ingress of overhead irrigation water to the root zone of transplants, thus reducing the amount of overhead irrigation needed for stand establishment.

Ag Order 4.0 was approved in 2021 and took effect in March 2023. In the first year, 500 pounds of nitrogen per acre can be applied above what is removed by the crop. Under the water board’s Ag Order 4.0, this amount of nitrogen will steadily decrease until 2051, when a maximum of 50 pounds of nitrogen per acre after crop removal is allowed (Johnson, 2023). Ag Order 4.0 regulations are uncertain due to pending litigation on parts of the regulation. Cover crop nitrogen scavenging may help to mitigate some of the expected negative impacts of these regulations on growers (Brennan, 2024). Seawater intrusion has occurred in a few areas on limited occasions, especially during drought years. Plastics used for bed mulches and drip irrigation are under increased scrutiny and a search for suitable biodegradable plastics is ongoing but not yet realized.

Labor is a great source of uncertainty in farming, especially for crops like strawberry that rely extensively on hand labor. Strawberry production relies on labor for planting and harvesting and this makes up approximately 70% of all the costs associated with growing strawberries in California (Bolda et al., 2021). Labor and immigration laws greatly affect labor availability and its cost. The recent emphasis on automation is an attempt to improve labor efficiency and reduce the associated bodily stresses. Food safety concerns arise occasionally and have been met with award-winning training programs (Bellm, 2015) designed to train field workers in proper sanitation practices.

The California Department of Pesticide Regulation has embarked on a Sustainable Pest Management Roadmap (Sustainable Pest Management Workgroup, 2021). Beginning in 2025, this program aims to prioritize pesticides for reduction and support the change necessary to transition away from the use of high-risk pesticides in agricultural and nonagricultural settings. Some argue that this will accelerate the movement of agricultural regulation away from a science-based, risk/benefit management approach of optimizing food production toward a regulatory framework driven by more subjective social and political considerations. The ability of the California strawberry industry to optimize production under this challenging regulatory environment is uncertain (Strawberry Work Group, 2021).

A team of dedicated researchers and extension scientists at UC Davis, USDA Agricultural Research Service and Cal Poly are vigorously tackling these issues. The creation of the Strawberry Center at Cal Poly in 2014 is an example of the industry adapting to the increased need for research and extension activities in California strawberries.

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