The Transition to Monoculture in the United States Strawberry Industry

by

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Abstract

This dissertation analyzes the history and evolution of the United States strawberry industry from an economic perspective. Particular emphasis is placed on the location of production, the use of damage control, and the development of capital, elements which I argue gave rise to a system of strawberry monoculture. To do so, I take a multidisciplinary approach and draw on different bodies of literature to address key components of the industry's history, including the economic and biological rationale underlying agents' production choices, how emerging supply chains altered the organization of the industry, and the intransigence of production systems after they have been developed.

In Chapters 1 through 3, I provide a cursory overview of the origins of the strawberry industry, its production trends, key innovations, and its status leading up to and following the phaseout of the agricultural chemical methyl bromide. I also discuss the literature and methodological background I intend to draw upon; in particular, the evolution of agricultural systems, innovations and the development of new supply chains, and the economic and biological considerations of crop rotation and monoculture. I then introduce a more detailed depiction of strawberries prior to their commercialization, as well as the characteristics of proto-commercial production in the eastern US; this focuses on the confluence of key transportation supply chains and a breakthrough innovation in strawberry varieties, a combination which led to the formation of a full-fledged strawberry industry. I examine the structures that developed in response to this expansion as well as the costs and profits of a representative grower.

In Chapters 4 through 7, the focus of the historical narrative shifts from eastern and southern states to California. I provide a brief overview of the practice of fumigation and its development post-1850; in particular, I examine key fumigants and their uses, as well as their drawbacks, as context for the persistence of methyl bromide. I then discuss how California became the undisputed leader in national strawberry production, and how future innovations have been predicated upon the soil conditions provided by methyl bromide fumigation. I then use this contextual framework to construct a theoretical model of agricultural production in which an agent chooses between rotation and a chemical damage control agent.

In Chapters 8 and 9, I introduce the changes occurring to strawberry production in the post-war era, including several of the post-war innovations that depended on fumigation. I additionally fit empirical data to models of adoption suggested by economic literature. I conclude with a short overview of lessons derived from the historical narrative, including how key, seemingly immutable characteristics of strawberry production have persisted through the previous two centuries and continue to shape the industry.

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Contents

Chapter 1

Introduction

Over the past two centuries, strawberry production in the US has transformed from the foraging and gardening of a minor and highly-seasonal commodity into one of the most capital and resource-intensive agricultural industries in the country. Cultivation was once geographically widespread, each local or regional population center supplied by a handful of small districts nearby; now, production is concentrated into just a handful of districts which provide for consumption globally, an arrangement that heavily favors the highly productive districts of California's Central Coast. These changes have depended heavily on innovations in both transportation and refrigeration, without which strawberries could only be consumed locally. However, these innovations are also embodied in expensive, typically permanent infrastructure, which is why the modern industry has also been characterized by its relationship with the agricultural fumigant methyl bromide. Methyl bromide is a toxic but highly effective chemical used to eliminate soil-borne diseases, and is one of two chemicals included in a fumigation mixture known as MB/Pic. Soil fumigation with MB/Pic allowed growers to repeatedly cultivate to the same soil without the accumulation of pest pressure or a general loss in yields from a phenomenon known as the "replant problem." After methyl bromide was discovered to contribute to ozone depletion, it was scheduled to be phased out under the Montreal Protocol. Though this draw down period was extended until 2016 through the use of special exemptions, the industry has struggled to find a suitable replacement despite rising costs and stringent regulations. One key result of the following analysis is that high fixed costs of production encourage the adoption of monoculture; the loss of methyl bromide reintroduces geographic instability to cultivation, jeopardizing existing capital investments. In the sections that follow, we will examine and discuss the processes of technological change that have influenced the evolution of the industry: in particular, efforts to overcome perishability, to develop new and more robust supply chains, and to maintain a fixed location of production.

1.1 A Short History of Strawberries

Commercial strawberry production is an unexpectedly recent phenomenon. Although records of wild strawberry consumption stretch back for millennia, the domesticated species grown today are one of the youngest plants in modern agriculture. The contemporary strawberry (sometimes referred to as the "garden" strawberry) originated only 250 years ago, and was not adopted for large-scale production for over a century afterwards.[1] Commercial production in the U.S. began in the early 1800s, but remained anemic for decades until extensive railroad construction, rudimentary refrigeration, and the introduction of a strawberry cultivar called the Wilson resulted in a surge of interest and subsequent amateur speculation, creating a "strawberry fever" that spread throughout the United States and persisted for the next two to three decades. The Wilson was productive, climate-tolerant, and most importantly, able to self-fertilize, lowering knowledge barriers to entry and making cultivation economically viable in virtually any location that had access to a railroad. Acreage would increase 100-fold between 1850 and 1900.[2] This period has historically been considered the beginning of the modern commercial strawberry industry. California was at this time a minor producer - 4 to 8 percent of national production - and would remain so until after World War II.

The intersection of a post-war slump in traditional strawberry regions, the release of new varieties developed by the University of California, and the maturation of the frozen strawberry market would contribute to California's steadily increasing proportion of national production. Innovations in freezing and cold storage in the 1930s had created an outlet for strawberries in the new frozen produce market - they were both cheaper and available year-round, second only to frozen orange juice in popularity. However, it was only in the late 1940s/early 1950s when freezing capacity expanded at the retail and personal level that processors[3] could operate as a secondary outlet for growers. The University varieties, introduced in 1945, were not only high-yielding and disease-resistant, but their success could not be replicated in other states as they only thrived under California's climatic conditions. Further improvements to transportation supply chains - especially advances in refrigeration - made it physically possible for western growers to supply eastern markets, and with yields between two to four times higher than the national average, California growers were capable of competing with local producers throughout the country despite facing additional costs of transportation. By the 1950s, California accounted for 40 percent of national production.[4]

At the same time, however, California growers were also struggling with outbreaks of verticillium wilt, a fatal disease caused by the soil-borne fungus *Verticillium dahliae*. The disease, initially referred to as "brown blight" after the appearance of infected plants, had been recorded in California as early as 1912.[5] While verticillium has numerous, economically-valuable host crops, it is highly pathogenic to strawberries in particular - fatal wilting results from even minute levels of soil inoculum. Crop rotation proved entirely ineffective against verticillium's resting structures, or microsclerotia - they could remain dormant in the soil for over a decade, capable of returning to their active pathogenic state as soon as they encountered favorable conditions.[6] Strawberry growers in California were already effectively nomadic, growing one crop, rarely two, on a given plot of land before relocating to avoid the buildup of pests, disease, and yield losses associated with the "replant problem." Verticillium complicated this migration - cultivating new acreage became a gamble, and farmers began

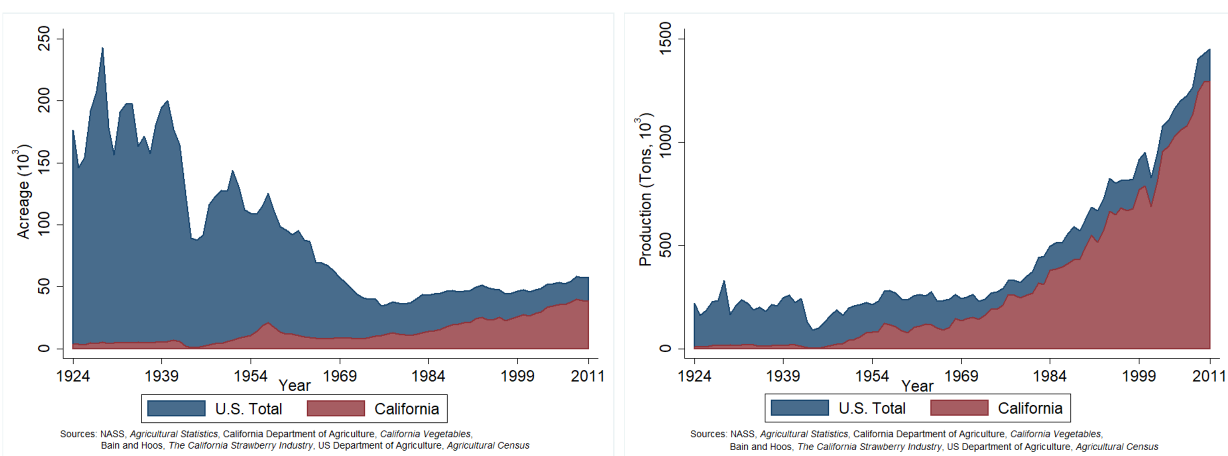
[1] Fletcher, *The Strawberry in North America*, p. 35.
[2] Ibid., pp. 34, 42, 50–51.
[3] "Processing" covers any non-fresh market usage. Originally, it referred to canning, but today it typically implies freezing.
[4] Bain and Hoos, *The California Strawberry Industry*, pp. 30, 48, 126–153.
[5] Tribble Bros., "California's Strawberry Culture", p. 653.
[6] Shipton, "Monoculture and Soilborne Plant Pathogens", pp. 1–2.

to avoid any land that included cotton or solanaceous[7] crops in its recent history.

Verticillium wilt was considered an existential threat to production, exacerbating land constraints in California's major strawberry districts and exposing growers to substantial economic risk until the development of methyl bromide/chloropicrin soil fumigation in the mid-20th century. In 1953, results from experimental fumigation in chrysanthemum production demonstrated that high quantities of chloropicrin - a re-purposed tear gas from World War I - could potentially destroy verticillium microsclerotia.[8] Strawberry trials were equally promising, but treatment was expensive and unpleasant; chloropicrin also volatilized poorly, limiting vertical soil coverage and making remediation inconsistent.[9] By 1960, plant pathologists had discovered that a mixture of chloropicrin and another fumigant, methyl bromide, was more effective even at two-thirds the application rate.[10] Methyl bromide was a comparatively poor fungicide, controlled weeds and pathogens while improving chloropicrin's soil mobility. By 1965, MB/Pic pre-plant fumigation was used to treat nearly 100% of new strawberry acreage, and was credited with stabilizing production, increasing yields, and streamlining breeding.[11] Its high cost expanded the productivity gap between California and other states, where returns on fumigation were too low to justify application. MB/Pic also made plasticulture feasible; covering strawberry beds with plastic sheets (or "mulch") increased yields considerably but prevented weeding by hand, requiring chemical treatment at the beginning of the season. Capital intensity rose as farmers expanded now-stationary operations; even as national acreage underwent a second contraction, lost yield was offset by sustained growth in productivity.

Figure 1.1: **Strawberries in the United States, 1924-2011**

(a) Acreage (b) Production



Strawberries today are the one of the most valuable fruits grown in the United States; in terms of total crop value, they are behind only grapes and apples as of the 2017 Agricultural

[7] This family includes the tomato, potato, eggplant, and pepper. Tomatoes and potatoes were the primary concern.

[8] S. Wilhelm and Sciaroni, "Verticillium in Chrysanthemum".

[9] S. Wilhelm, Richard Storkan, and J. Wilhelm, "Preplant Soil Fumigation", pp. 232–233.

[10] S. Wilhelm, *Bringing Our Knowledge Up to Date on Soil Fumigation, #4*.

[11] S. Wilhelm, Richard Storkan, and J. Wilhelm, "Preplant Soil Fumigation", pp. 234–235.

Census. Slightly more than 70 percent of all commercial strawberry acreage is located in California, primarily along the Central Coast. Another 17.5 percent was grown in Florida, and the remainder was split between the Pacific Northwest and some minor production in New York and North Carolina. California still produces a disproportionately high 90 percent of all strawberries in the United States.[12] Strawberry farms themselves have always been comparatively small but are now extraordinarily capital intensive, possessing one of the highest per-acre asset values in U.S. agriculture. Productivity is also an order of magnitude greater than at the beginning of the 20th century, with yields in California commonly falling anywhere between 30 to 50 tons an acre.[13]

1.1.1 The Phaseout of Methyl Bromide

However, there has been widespread concern over the long-term viability of the status quo with the loss of the agricultural fumigant, methyl bromide, which was finally phased out in 2016. Since its introduction in 1960, methyl bromide has widely regarded as an agricultural "silver bullet,"[14] but by the mid-1980s, researchers had discovered atmospheric methyl bromide photodegraded into bromine oxide: a Class I ozone depleting substance, subject to regulation under the Montreal Protocol. In 1994, the US Environmental Protection Agency capped methyl bromide production and import at 1991 levels, and scheduled it to be phased out by 2005.[15] This decision met with organized resistance from the agricultural sector, especially the California strawberry industry.[16] They were partially successful, and certain industries - including California strawberry growers - were granted temporary Critical Use Exemptions (CUEs) if there were no economically or technically feasible alternatives. Although the last CUEs for soil fumigation were issued in 2016, methyl bromide usage persists in quarantine/pre-shipment fumigation - as one of two primary fumigants for agricultural produce, its role in preventing the spread of invasive species was considered too critical to eliminate. This has created an edge case in strawberry production: nurseries require phytosanitary certification[17] to supply growers, and have maintained access to methyl bromide since nursery fumigation falls under quarantine regulation. The stability of this arrangement remains uncertain.

The phaseout has proved controversial in several regards. For its users, methyl bromide was key to successful production, and it was christened a "miracle gas" even before it could be applied effectively as a soil fumigant.[18] A single treatment controlled a broad spectrum of economically-relevant pests, including weeds, nematodes, and (with chloropicrin), fungi. This has made it indispensable to nurseries as well as specialty crops, but the viability of alternatives - or lack thereof - threatens to disrupt production. Economic pressure is escalating; growers are struggling with the resurgence of what had hitherto been unimportant diseases,

[12] *National Agricultural Statistics Service*, Accessed 12-30-2019.

[13] USDA, 2017 Agricultural Census, "Selected Characteristics of Farms," table 48, p.59

[14] German, "Post Methyl Bromide Era".

[15] Morrissey, *Methyl Bromide and Stratospheric Ozone Depletion*, pp. 1–4.

[16] Goldschein, "Methyl Bromide", pp. 603–606.

[17] "Phytosanitary" refers to the measures taken to protect local plant health, typically with regard to the import/export of plants and the prevention of invasive species.

[18] R. H. Taylor, "The Farmer's Corner".

such as *Macrophomina phaseolina*, or “charcoal rot,” which existing methyl bromide alternatives do not appear to adequately control. To minimize the impact to growers, significant effort has been devoted to finding a suitable “drop-in replacement” - a chemical that can be inserted into the existing system without requiring user adaptation, similar to components in a computer. For new treatments, like ethanedinitrile (EDN), this involves developing application methods, assessing efficacy, and provided the results are promising, applying for registration. Another possibility is improving the efficacy of previously-available fumigants, such as Pic-Clor (chloropicrin mixed with 1,3-Dichloropropene, a nematicide) applied under impermeable films,[19] which maintain lethal fumigant concentrations for a longer duration.[20] Experiments with non-chemical alternatives like soil solarization, steam or anaerobic soil disinfestation, or rotation with crops in the brassica[21] family have had encouraging results, but most are only viable under an extremely narrow set of conditions. The path forward, whether it be a suitable replacement or an overhaul of production practices, is still unclear.

In contrast, others have vehemently condemned the structure of the phaseout - methyl bromide’s continued usage is a subversion of the intended goals of the Montreal Protocol and a matter of public concern. Farmer inaction is considered culpable for delays in the adoption of alternatives and has impeded their development. These concerns have a long history - as early as 1967, newspapers published advertisements for fruit and vegetable decontamination washes in order to remove pesticide residues.[22] As recognition of the effects of pesticide exposure has grown, public aversion to their use has followed suit. Mounting disapproval and anxiety over strawberries’ close relationship to fumigation is crystallized in articles like “*The Berry and the Poison*” (Smithsonian Magazine, Dec. 1996), or more recently, “*Almost All American Strawberries Are Grown With Toxic Chemicals*” (The Atlantic, Sept. 1, 2019). Julie Guthman dissects this entanglement in her book, *Wilted*, paying particular attention to the co-dependencies between methyl bromide and other aspects of the industry that have evolved as a result. This reaction to methyl bromide is not without cause. The Environmental Working Group includes strawberries in the “Dirty Dozen” - the twelve fruits and vegetables with the highest pesticide residues. Pesticide drift has become an ever-present concern as “buffer zones” - spaces between agricultural and residential areas - have been shaved away by suburban expansion and shifting populations. Methyl bromide was central to a legal settlement in 2011; the Environmental Protection Agency’s Office of Civil Rights sued the California Department of Pesticide Regulation over the disproportionate amount of soil fumigation near Latino communities. To many, methyl bromide’s deleterious impacts on human health, the environment, and the potential for accidental exposure are unacceptable no matter the efficacy.

[19]There are two types of “impermeable film” - virtually impermeable film (VIF) and totally impermeable film (TIF). They use an internal barrier between two layers of plastic to reduce gas permeability of the sheet - VIF uses a nylon polymer, while TIF uses ethylene vinyl alcohol. TIF is less permeable than VIF, but both are improvements over traditional low-density polyethylene.

[20]Many of these experiments and their assessments are presented at the annual Methyl Bromide Alternatives Outreach conference, and can be read about on their website: https://www.mbao.org/

[21]Broccoli, cauliflower, Brussels sprouts, etc.

[22]San Bernardino Sun, “Advertisements”.

1.1.2 Methyl Bromide's Persistence

Despite public reaction to methyl bromide, its rapidly increasing cost, and the millions of dollars invested in researching and developing alternatives, it remained indispensable to strawberry production. Methyl bromide has been described as "not a spoke in the wheel, but the axle" - without it, the structure begins to collapse in on itself. Previous technological changes had resulted in overtures to a system of monoculture; new varieties, faster transportation, and effective refrigeration would extend the geographic range of cultivation immensely, but within those new districts growers would naturally cluster around shipping and cooling facilities to improve economic outcomes. However, this was not a stable equilibrium, as pest pressure and soil issues began to accumulate and growers began to seek out new land to cultivate. By resolving these issues, methyl bromide allowed for greater spatial concentration, stable production, and higher capital investment both on and off-farm, and was thus the catalyst that allowed California to eventually claim 90 percent of the market. Methyl bromide's spatial effects are apparent in the immediate aftermath of its introduction: a steady, decade-long decline in acreage, and a redistribution of this acreage to southern California and the Central Coast. Stability of production and capital investment are also directly related; this is reflected in the development of permanent or semi-permanent external strawberry capital, including shipping facilities, processors, and fumigation services, all of which require sufficient production within a given area to be practical investments.

To our knowledge, most of the economic literature concerning crop rotation focuses on the yield benefits from soil fertility and reductions in pest and disease pressure, presenting it as an alternate system to an existing pesticide regime. A limited number of papers also address either the influence of capital on cropping decisions or the development of external capital that emerges in regions of intensive production, such as Spera, VanWey, and Mustard (2016)[23] and Park, Anderson, and Thompson (2019)[24]; however, they do not investigate or discuss the potential relationship between this capital and the practice of crop rotation. The argument motivating this dissertation is that methyl bromide's integral nature in the functioning of California's strawberry industry stems directly from the adoption of monoculture. In addition, methyl bromide demonstrates the causality of this relationship in some instances occurs in the opposite direction of conventional wisdom. For strawberries, pesticides were not adopted as a result of monocultural production, but rather they **enabled** growers to transition to such a system.

1.2 Related Literature

This historical narrative is comprised of several intertwined themes of agricultural progress, including the evolution of agricultural systems, technology and its role in the creation of new supply chains, and the linkages between crop rotation, pest control methods; for clarity, these general elements and their development throughout the industry's history are briefly laid out in Tables 1.1 and 1.2 on pages 7 and 8. Early cultivation exhibited many of the characteristics theorized by literature on agricultural progression - although strawberries

[23]Spera, VanWey, and Mustard, "The Drivers of Sugarcane Expansion in Goiás, Brazil".

[24]Park, Anderson, and E. Thompson, "Land-Use, Crop Choice, and Proximity to Ethanol Plants".

Table 1.1: Abbreviated Trends in 19^{th} Strawberry Production

Years	Thematic Elements		
	Development of Supply Chains	Location of Production	Intensification and Technological Adoption
Pre-1800s	Single stage chain; harvesting, with some forage sold in urban areas. Season is highly compressed; 2-4 weeks long.	Solely in forested regions and fields. Wild berries are abundant near newly colonized areas.	Consumers reliant on forage and minimal gardening. Horticultural experiments limited to Europe.
1800-1830	National roads built; minimal benefit for strawberries, virtually no interregional trade. No marketing; farmers sell own produce. Nurseries import European cultivars.	Local forage is still primary source for all consumers (> 90% of supply). Any marketed production occurs very close to large cities: Boston, New York, Baltimore, Cincinnati.	Commercial production is extremely small in scale, coexists alongside market gardening. Domestic experiments with fertilizers/soils. Very limited use of hothouses for "forcing."
1830-1850	Canals/steamboats provide growers near waterways ability to ship to coastal cities. Limited in application. Strawberry breeding develops in U.S. following the Hovey cultivar.	Production expands near New York, Boston. Cincinnati emerges as important producer, displaces NYC as main strawberry market for a few years. Virginia ships small amounts north by water.	Hovey cultivar and intensive cultivation adopted around Boston. New understanding of strawberry sexuality increases yields and yield reliability by mid-1840s.
1850-1870	Extensive construction of railroads, experiments with rudimentary refrigeration. Farmers contract with shippers, commission merchants; telegraph informs them of distant market conditions.	Production expands along new railroads, extends hundreds of miles outside cities. Forage replaced by cultivation. Production gradually moves southward; Pacific Coast industries emerge in isolation.	Introduction of the hardy, bisexual Wilson cultivar causes massive increase in cultivated area; allows for broader climatic range of cultivation, encourages adoption of extensive practices.
1870-1900	By end of century, rail improvements, more icing facilities, and canning extend viable shipping range.	Prior to rail improvements, reliability issues (delays, shipment coordination) and low prices had created focus on "home" markets.	Pest pressure develops towards end of 19^{th}/start of 20^{th} century; includes insect predation and leaf rust (fungus).

Table 1.2: Abbreviated Trends in 20^{th} Century Strawberry Production

Years	Thematic Elements		
	Development of Supply Chains	Location of Production	Intensification and Technological Adoption
1900-1930	Cold storage and better refrigeration smooth out shipping disruptions in supply chain. Wider geographic distribution extends market season by several weeks.	Production concentrates in south. Two distinct producer groups - home market (local) producers and shippers. The latter clusters near transport facilities, markets to urban centers.	Growers in southern states tend to be low-intensity, high-acreage producers; cultivation relocates rather than preserve soil quality. Over time, acreage near shipping facilities degrades.
1930-1940	Quick-freezing alters agricultural supply chains, and new frozen berry market emerges. Retailers and consumers have limited capacity for frozen product storage.	Majority of production occurs in the Central South, which cultivates high acreage but has low productivity. Intensity increases with proximity to Gulf Coast, Florida.	Frozen strawberries become second market outlet; overcomes spoilage, avoids weight drawback of canning. Limited California adoption; lower costs in Pacific NW.
1940-1960	Post-war, frozen supply chain in California develops. Marketing to eastern states begins in earnest. First air shipments of strawberries from California begin in late 1950s/early 1960s.	Slow post-war recovery of strawberry production outside California. California leads fresh market with nearly 50 percent market share. Frozen berry market almost entirely dominated by Pacific Coast.	In California, introduction of University varieties, new planting systems, plasticulture, fumigation with chloropicrin and later methyl bromide.
1960-1970	Within California, increased importance of nursery supply chain; more companies providing fumigation services.	Fresh market production increasingly concentrated in California, where acreage shifts to coastal/southern districts post-fumigation.	California acreage declines, but outpaced by increase in yields. Drip irrigation introduced by end of decade.

were initially foraged, not cultivated, the transition from harvesting to farming was driven by population growth and a reduction in available land. Later, intensification and the adoption of annual cropping were instead driven by increasing demand and technological innovation. Systems of cultivation developed to overcome severe spatial and temporal constraints; the incorporation of railroads and simple ice-based cooling mechanisms fundamentally altered the existing farm-to-consumer supply chain, decoupling farmers from land near urban centers during the late 19$^{\text{th}}$ century. This marked the beginning of a southward trend in strawberry cultivation; warmer climates increased yields, the earliness of production, and the length of the bearing season. Despite these advantages, strawberries' fragility continued to ensure a role for local production well into the 20$^{\text{th}}$ century. We will briefly examine each of these literatures in the following section.

1.2.1 Agricultural Systems

The history of the strawberry industry is characterized by the evolution of a low-intensity agricultural system oriented to local and personal consumption to a highly specialized global commodity, a phenomenon that has been addressed both theoretically and empirically in a substantial body of literature. Broadly speaking, the evolution of agricultural systems has been divided into three stages. The first is the development of agriculture itself - the transition from systems of "harvest" (hunting, gathering, fishing) to systems of farming. The second is the expansion of agricultural production, or extensive growth - as demand for agriculture increases, more land will enter into cultivation. The third stage is increasing agricultural productivity, or intensive growth, where further demand for agriculture is met by increasing productivity rather than by expanding. Ester Boserup, in her 1965 work *The Conditions of Agricultural Growth*, argues that the entire history of agricultural evolution can be linked to increasing population density. According to Boserup's theory, a hunter/gatherer society is first compelled to adopt agriculture as a result of population pressure, and further growth eventually encroaches on fallow land used for rotating crops. Agricultural labor necessarily increases as farmers shift from extensive to intensive land use, and long fallow periods become progressively shorter until they are replaced with systems of annual production or even multi-cropping. Land use transition requires higher investment (such as irrigation) on some fields and entails moving others out of production.[25]

Zilberman et al (2013) characterize the transition from systems of harvest to systems of farming as a redistribution of effort between stages of production. Farmers invest in cultivation and husbandry - earlier points in the production process - to reduce the search and harvest costs they would otherwise face as hunter/gatherers.[26] Berck and Perloff (1985), in their work on fisheries, found that in some circumstances the existence of harvest systems can impede the emergence of farming. Their model indicates that harvesting of open-access commons potentially creates a barrier to entry for fish farms: the new supply equilibrium after entry may cause fish prices to decline, dissuading rational farmers from entering the market.[27] Carlson and Zilberman (1993) modeled the emergence and eventual dominance of

[25]Boserup, *The Conditions of Agricultural Growth*, pp. 8–12, 43–44.
[26]Zilberman, Kim, et al., "Technology and the Future Bioeconomy".
[27]Berck and Perloff, "Why There Are so Few Fish Farms".

farming systems as a result of increasing demand exceeding the capacity of harvesting. They suggested that cost reductions via technological innovations will occur far more rapidly under the farming system.[28] Boserup's theory similarly claims that innovation diffusion depends on the rate of population growth. Gradual increases allow multiple "levels" of cultivation intensity to coexist, while rapid change will lead to faster replacement.[29]

Agricultural intensification has been indisputably beneficial for social welfare, as the use of enhanced seeds, artificial fertilizers, synthetic pesticides, and irrigation technology has improved food security for the impoverished on a global scale. However, the environmental impact remains ambiguous. Environmentally detrimental side effects of many productivity-enhancing technologies are well-documented; for instance, the use of pest control disrupts ecological communities, particularly when the treatment is non-selective. Repeated use creates evolutionary pressure for resistance, eventually requiring the development of new compounds, though in the interim farmers respond to loss of pesticide efficacy by increasing application rates.[30] Even relatively benign technologies are implicated in environmental damage - fertilizer runoff can cause eutrophication in nearby waterways, while irrigation can lead to the degradation of soil over time through increased salinization.[31] In some regions, the severity of these issues has called into question the long-term sustainability of intensive agriculture. On the other hand, there have also been a host of environmental benefits. Intensive agriculture has been shown to be land-sparing - preventing forests, fields, or otherwise untouched land from entering into cultivation, preserving ecosystem services and natural habitats. In addition, despite the carbon footprint of mechanization and artificial fertilizer, these technologies are carbon-saving in comparison to the extensive-production alternative.[32] Genetically modified seeds have also maintained yields while reducing environmental damage. Herbicide-tolerant (HT) seeds, in concert with the use of post-emergent herbicides,[33] have increased farmer adoption of conservation tillage, thereby indirectly reducing erosion, carbon emissions, and soil deterioration.[34]

1.2.2 Supply Chains and Innovation

The body of supply chain literature is also central to our discussion of the strawberry industry; as we will examine in later chapters, much of the progress in strawberry production has resulted from innovations that relax the strict spatial and temporal constraints on such a perishable fruit, often requiring or resulting in substantive changes to existing supply chains. The agricultural sector as a whole is governed by an interconnected network by which raw materials, or feedstock, are converted into finished products by intermediary processors before they reach consumers. In its simplest form, an agricultural supply chain may consist of just three components: a processor, a source of feedstock, and an end market. However,

[28] Carlson and Zilberman, "Emerging Resource Issues in World Agriculture", pp. 492–497.

[29] Boserup, *The Conditions of Agricultural Growth*, pp. 46–56.

[30] Knight and Norton, "Agricultural Pesticide Resistance".

[31] Matson et al., "Agricultural Intensification".

[32] Burney, S. Davis, and Lobell, "Greenhouse Gas Mitigation".

[33] "Post-emergent" herbicides are applied to weeds that have already germinated. The most common of these is glyphosate, also known as *Roundup*.

[34] Fernandez-Cornejo et al., "Conservation Tillage".

agricultural innovations have allowed farmers to trade self-sufficiency for greater specialization, and the average supply chain has lengthened as farmers acquire seeds, fertilizer, and pesticides from outside sources. These innovations are themselves intimately linked to supply chains, as their development and deployment often requires innovators to redesign existing supply chains or create entirely new ones. An innovator may decide to produce their own feedstock, rely on outside contracting, or some of the two. If they are able to exert market power over feedstock suppliers, like strawberry shippers or freezers, they will rely more heavily on contracting - provided that the elasticity of marginal cost of capital is less than the elasticity of marginal cost of third-party supply.[35] Technological progress in supply chains has also increased the number of agricultural producers in competition with one another, emphasizing the importance of product differentiation; in turn, these differentiated products often require the development of their own supply chains.[36]

The supply chain literature has its roots in earlier location economics and theories of production specialization. In the 1800s, the German economist Johann Heinrich von Thunen derived his theory of agricultural location and intensity from his observations of farmers shipping goods to market. He proposed that cropping decisions and cultivation intensity were governed by freight costs and land rental rate, both of which were determined by distance to a single central market in von Thunen's "isolated state." The closer a farmer was to the market, the more valuable their produce or the more intensive their cultivation. At the beginning of the 1900s, Alfred Weber proposed a similar model based on industry cost-minimization; the owner of a firm selects the location of a facility based on relative transportation costs of input and output. Similar to Von Thunen, this decision depends on material weight, but also on the benefits from industry agglomeration and labor acquisition.[37] As transportation costs diminish, however, other productive factors become relatively more important. Technological improvements in transportation lead to greater agricultural specialization, as natural variation in land quality is weighted more heavily in farmers' cropping decisions.[38] Dennis and Sammet (1961) would demonstrate this empirically in their analysis of strawberry processing facilities. Despite the distance between California production and the eastern market, local yield advantages lowered production cost enough to compensate for the majority of transnational shipping expenses.[39]

The newfound emphasis on supply chain design and performance is a consequence of new innovations and increased globalization, which have increased supply chain length as well as complexity.[40] In agriculture, for example, railroads and highways have steadily increased the distance between farmer and consumer, enabling production on land best suited for a given crop. This supply chain is also completely dependent on consistent, effective refrigeration - at such distances, any interruptions in the cold chain lead to spoilage. Du et al (2016) discuss the supply chain of an innovative agricultural firm wielding both upstream and downstream market power, which has to strike a balance between investment in processing capacity versus their ability to produce their own feedstock. Vertical integration may allow them to

[35] Du et al., "Agricultural Supply Chain Design", pp. 1379–1382.

[36] Zilberman, Lu, and Reardon, "Innovation-Induced Food Supply Chain Design".

[37] Capello (2013) discusses both of these foundational models in detail.

[38] Brinkmann, *Economics of the Farm Business*.

[39] Dennis and Sammet, "Interregional Competition".

[40] Beamon, "Supply Chain Design", pp. 2–3.

exercise monopsony power when acquiring feedstock from third party suppliers, but credit constraints may require them to balance feedstock production against processing capacity.[41] Agricultural intensity also plays an important role in supply chain formation. Zilberman et al (2017) suggest that higher degrees of specialization require processors to contract suppliers rather than produce in-house, lengthening the requisite supply chain for feedstock.[42] This dissertation will demonstrate that transportation innovation - trains, trucks, and particularly refrigeration - have enabled longer supply chains and specialization in production.

Learning

An important aspect of technological innovation is the process in which present or future adopters of the innovation develop a knowledge base, accumulating human capital through personal experience or observation. This is referred to in economic literature as "learning by doing," and improves the performance of an innovation over time. Thomas Schultz (1961) would discuss this accumulation in the context of education, emphasising the importance of investing in its development and maintenance; the same year, Kenneth Arrow (1961) would address learning by doing more formally by incorporating it in a production model.[43,44] More recently, Wolf et al (2001) discussed the critical role of public agencies in producing this information and coordinating its distribution.[45] Learning by doing can be observed throughout the history of strawberry cultivation, heavily influencing the cultivation practices of growers. Early cultivation efforts were in constant flux, with practices adopted or abandoned based on individual trial and error. Later, regional publications began to disseminate experiential learning and the results of horticultural research over a wider geographic area, a role which was eventually occupied by government agencies.

Transformation of Agriculture

There is also a growing body of literature on the transformation of agriculture in developing countries. Barrett et al (2020) provide both overview of the subject as well as previous research, which includes the transfer of knowledge and the adoption of innovations from developed countries as well as the the emergence of an "agri-food value chain" (AVC) comprised of post-farm services such as processing, storage, and retailing.[46] Both of these threads feature prominently in the development of the strawberry industry. Cultivation practices and varieties were initially derived from European horticulture; although European approaches would prove less than ideal in the North American climate, they would influence strawberry growing well into the 19$^{\text{th}}$ century. As cultivation became increasingly sophisticated, so too did the AVC of strawberry production: personal and local distribution were replaced by auction houses and freight services; in-home preserving was superseded by new processing facilities, first fruit drying, then freezing; and on-farm sheds for preventing sun damage were

[41] Du et al., "Agricultural Supply Chain Design".

[42] Zilberman, Lu, and Reardon, "Innovation-Induced Food Supply Chain Design".

[43] Schultz, "Investment in Human Capital".

[44] Arrow, *The Economic Implications of Learning by Doing*, pp. 1–5.

[45] Wolf, D. Just, and Zilberman, "Between Data and Decisions: The Organization of Agricultural Economic Information Systems".

[46] Barrett et al., "Agri-food Value Chain Revolutions in Low-and Middle-Income Countries".

largely made obsolete by refrigerated transit and cooling facilities. These value chains have fundamentally changed methods of production and distribution, and are what have allowed districts in California and Florida to become global suppliers of strawberries.

1.2.3 Crop Rotation, Pest Control, and Monoculture

Crop rotation is a long-established agricultural practice that involves the production of different crops in sequence or fallowing a field between plantings. Kollas et al (2015) provide a well-documented list of the farmer-level benefits of rotation, including pest pressure reduction through habitat interruption, the restoration of soil fertility (often through legume rotations), and erosion prevention through improvement of soil structure. At the system level, rotation can increase agricultural resilience to climate change and improve available ecosystem services.[47] Ideally, sequenced crops deplete different soil nutrients, are not predated on by the same species, and have compatible capital requirements and seeding/harvesting schedules. Adverse rotations - crops with overlapping schedules or disparity in land preparation - will add to production costs or otherwise impede cultivation.[48] The absence of rotation, on the other hand, will eventually culminate in reduced long-term productivity, potentially leaving the soil unsuitable for future agriculture. As Boserup explains, the benefits of crop rotation have been understood since antiquity, yet the practice was adopted only when the necessity of higher yields justified the increased labor requirements.[49]

Despite the importance of rotation, monoculture[50] has become steadily more attractive for growers since the early 1900s. In their *Scientific American* article, J.F. Power and R.F. Follett of the Agricultural Research Service stated that "where monoculture is dominant, a supporting economic and material infrastructure usually develops, reinforcing the position of the dominant crop."[51] Mechanization has allowed farmers to cheaply cultivate greater amounts of acreage, with the added benefit of eliminating production of draft animal fodder. Specialized agricultural equipment and improved varieties of crops further discouraged long rotation sequences, while the availability of off-farm services reduces the importance of self-sufficiency and the amount of machinery a farmer has to invest in. The production of single crops simplifies supply chains and marketing efforts. Synthetic fertilizers and pesticides have also allowed farmers to compensate for the damage caused by poor rotation practices, effectively replacing the need for sequence planning and capital variety with new inputs. In response to these conditions, farmers have reduced the length of their rotations overall, and in some cases have eliminated them completely.[52]

Pest control[53] as both practice and science has accelerated rapidly over the past half-century. Farmers, ignorant of the long-term effects of bioaccumulation and environmental persistence, used new synthetic pesticides liberally and to the detriment of themselves, their

[47] Kollas et al., "Crop Rotation Modelling - A European Model Intercomparison".

[48] Hennessy, "Monoculture and the Structure of Crop Rotations".

[49] Boserup, *The Conditions of Agricultural Growth*, pp. 28–29.

[50] The strict definition of monoculture is somewhat murky. To avoid this issue, we will regard monoculture as an umbrella term under which agricultural practices may exhibit some variation, such as in Shipton (1977).

[51] Power and Follett, "Monoculture", p. 82.

[52] Ibid.

[53] Although "pest control" extends to numerous methods of eliminating or deterring pests, agricultural economics is primarily concerned with chemical methods.

crops, and their surroundings. Consequences included severe health impacts for workers (particularly cancer and birth defects), elevated residues on food crops, and persistent ecological disruption and contamination. Overuse of pesticides had also created evolutionary pressure for resistance in a number of species. Stern et al (1959) were the first to introduce the concept of an "economic injury threshold" as an alternative to fixed schedules of pesticide applications - a reactive, rather than proactive system, where pesticides were applied only when target pests reached an economically-relevant density.[54] In a similar vein, Hillebrant (1960) analyzed pesticide usage in the context of profit maximization, deriving an optimal application rate based on crop prices, chemical and application costs, and the dosage-response curve of a target pest. Notably, pesticide applications had diminishing marginal returns as a pest species was eliminated, thus arriving at the same result of Stern et al.[55] However, unlike traditional productive inputs, such as water or fertilizer, pesticides reduce yield loss instead of increasing output. Lichtenberg and Zilberman (1986) were the first to treat pesticides as "damage control agents," an input into a function of abatement rather than production. They argued that by treating pesticides as yield-improving inputs, previous specifications had overestimated their true marginal value.[56] Their conclusion has generated some debate (see Carpentier and Weaver, 1996), but is arguably a better approximation of biological reality. Since the 1970s, pesticides have been regulated by the Environmental Protection Agency under amendments to the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA), under which focus has shifted from ensuring efficacy to protecting human and environmental health. Pesticides are now registered with the EPA and are subject to a battery of toxicological studies prior to distribution. Registration is not permanent; products may be withdrawn by the manufacturer or deregistered if new information reveals they pose unacceptable risk. Revoking a pesticide's registration can cause significant disruption if alternatives are unavailable or not economically feasible. Zilberman et al (1991) discuss the impact of different pesticide regulations on grower and consumer welfare - specifically, the trade-offs between an outright ban on a chemical or group of chemicals versus alternative policies, like fees or restrictions on use.[57]

Crop rotation and pesticide use are integral to the history of the strawberry industry, particularly with regard to the regulation and phaseout of methyl bromide, and a large body of literature has emerged to address the impact of these policies. In anticipation of the phaseout, Yarkin et al (1994) estimated the potential loss of net farm income and suggested welfare-improving alternatives to an outright ban.[58] Carpenter, Gianessi, and Lynch (2000) provided a comprehensive analysis of several key crops and the expected effect on yields, grower revenue, and the distribution of acreage.[59] Carter et al (2005) focused on the California strawberry industry and how the impact would be distributed within the state based on time of production during the year.[60] This literature also extends to potential alternatives; multiple papers - Fields and White (2002), Kabir et al (2005), Sydorovych et al (2006),

[54]Stern et al., "The Integrated Control Concept".

[55]Hillebrant, "Economic Theory of the Use of Pesticides, Part 1".

[56]Lichtenberg and Zilberman, "Econometrics of Damage Control".

[57]Zilberman, Schmitz, et al., "The Economics of Pesticide Use and Regulation".

[58]Yarkin et al., "All Crops Should Not Be Treated Equally".

[59]Carpenter, Gianessi, and Lynch, *The Economic Impact of the Scheduled U.S. Phaseout of Methyl Bromide*.

[60]C. Carter et al., "The Methyl Bromide Ban: Economic Impacts on the California Strawberry Industry".

Ducom (2012) - have discussed the economic viability of both drop-in chemical replacements as well as cultural overhauls.[61,62,63,64] That this literature has continued to expand over the past three decades speaks to the difficulty in finding an equivalent replacement for methyl bromide, and motivates a significant portion of this dissertation.

[61] Ducom, "Methyl Bromide Alternatives".

[62] Fields and N. White, "Alternatives to Methyl Bromide Treatments".

[63] Kabir et al., "Alternatives to Methyl Bromide for Strawberry Runner Production".

[64] Sydorovych et al., "Economic Evaluation of Methyl Bromide Alternatives".

Chapter 2

Pre-Commercial Production

Wild strawberries have been gathered for centuries in the Western hemisphere, if not millennia - references to the fruit are found in Roman poetry and Native American recipes.[1] The strawberry would remain a fruit of the wilds until the 14th century, after which Europeans began transplanting them to their personal gardens. They cultivated the wood strawberry, *Fragaria vesca*, a diminutive plant that produced round fruit roughly half an inch in diameter. Stevenson (S.W.) Fletcher, a professor of horticulture and author of *The Strawberry in North America*, suggested European cultivation emerged as a response to urban expansion displacing wild strawberry habitat. The impetus behind cultivation would evolve over the next few centuries, shifting first from ornamental gardening to medicinal purposes, then finally for personal consumption. By the 16th century, two other indigenous European species - *Fragaria moschata* and *Fragaria viridis* - had been recorded. *F. vesca* and its related subspecies were a regular appearance in household gardens, marking the beginning of what Fletcher termed "garden culture." Crop husbandry required greater effort than foraging, including the transplanting, hoeing, and fertilizing of strawberry beds, but rewarded farmers with larger and more reliable fruit as well as the opportunity for financial returns. Garden culture additionally generated a newfound interest in strawberry botany, and European horticulturists soon turned their focus outward to the breeding and cultivation of varieties from other continents. Their efforts had long-term, paradigm-shaping implications; today, strawberry cultivation is almost entirely based on descendants of the hybrid *Fragaria x ananassa*,[2] which resulted from a cross of the indigenous Virginian and Chilean wild strawberries imported to Europe in the 17th and 18th centuries.[3]

F. ananassa is one of the youngest domesticated plants currently grown, and it embodied significant advances in the botany of strawberries, specifically with regards to their sexual characteristics.[4] Wild varieties, including the Chilean and Virginian, generally exhibit gender dimorphism and male sterility; although the importance of the distinction was not understood until the middle of the 18th century, it had serious ramifications for early strawberry horticulture. Botanists had mistakenly classified strawberries as hermaphroditic, and in the course of their research abroad they had selected what they believed were productive wild samples to bring back and cultivate in Europe.[5] Unknowingly having taken only

[1] S. Wilhelm and James Sagen, *A History of the Strawberry*, pp. 20–22, 61.

[2] *F. ananassa* is the "Pineapple" or "Pine" strawberry, named for its aroma.

[3] Darrow, *The Strawberry*, pp. 15–23.

[4] Liston, Cronn, and Ashman, "Fragaria".

[5] Fletcher, *The Strawberry in North America*, p. 94.

fruit-producing female plants, they soon discovered that these samples were rarely as prolific as they were in their native habitat. Gardeners who adopted these varieties for cultivation made similar decisions, culling unproductive male plants only to find that their fields were becoming increasingly barren.[6] Experimental observations by the French botanist Antoine Duchesne in 1765 led to three important theories: first, that strawberries did in fact express sexual dimorphism, second, that female plants (pistillate flowers) required pollination from males (staminate flowers) in order to produce fruit, and third, that not all varieties could cross-pollinate. Duchesne applied these theories to crosses of the large-fruiting Chilean and Virginian cultivars, resulting in a number of hermaphroditic, self-fertilizing hybrids - likely the first *F. ananassa* ever intentionally created.[7] Evidence indicates that Duchesne's observations were slow to circulate outside of France - English gardeners appear to have identified strawberries' dimorphism independently in the early 1800s, roughly 50 years later.[8]

In the American colonies, there was no serious strawberry cultivation to speak of prior to the 1700s. The abundance of the indigenous Virginian strawberry had suppressed American interest in cultivation, with the wild harvest providing ample supply for both local market vendors and personal consumption. By the middle of the century, however, urbanization and cultivated agriculture had started to encroach on regions of wild strawberries; as labor and time costs of foraging increased, Americans began transplanting wild varieties into their personal gardens.[9] This displacement also coincided with the establishment of the first American nurseries, but since there had been no domestic effort to improve upon existing cultivars, they only imported and marketed plants developed by European breeders. Domesticated strawberries were limited to a small handful of varieties, including the Chilean, the Hautbois, and variations of the Virginian - *Fragaria x ananassa* had yet to be imported.[10] Their fruit was often significantly larger than their wild cousins, and under the right conditions they could also be far more productive.[11]

American garden culture developed in the late 1700s, but was restricted to the vicinity of larger urban areas. The overwhelming majority of Americans lived on farms or in rural communities and relied on wild strawberries well into the next century. Despite their success in Europe, the Chilean and Hautbois strawberries were unpopular varieties and poorly suited for cultivation in the United States.[12] The Chilean was climate-intolerant and performed poorly without significant care - later, Fuller (1887) would remark that, "with few exceptions, these are of little value for cultivating in this country."[13] Despite the Chilean strawberry's large size - often likened to that of a hen's egg or small plum - it was also known for its inferior texture and flavor.[14] The Hautbois variety was even less desirable - considered "disagreeable" in both odor and flavor, it was relegated to cultivation in botanical gardens.[15] More generally, strawberry production under the American system was discour-

[6] Darrow, *The Strawberry*, pp. 30–36.

[7] Liston, Cronn, and Ashman, "Fragaria", pp. 1691–1692.

[8] Peacock, *Profits in Strawberry Production*, p. 4.

[9] Fletcher, *The Strawberry in North America*, pp. 4–7.

[10] Randolph (trans)., *The Parlor Gardener: A Treatise on the House Culture of Ornamental Plants*, pp. 45–46.

[11] S. Wilhelm and James Sagen, *A History of the Strawberry*, pp. 136–143.

[12] Fletcher, *The Strawberry in North America*, pp. 6–7.

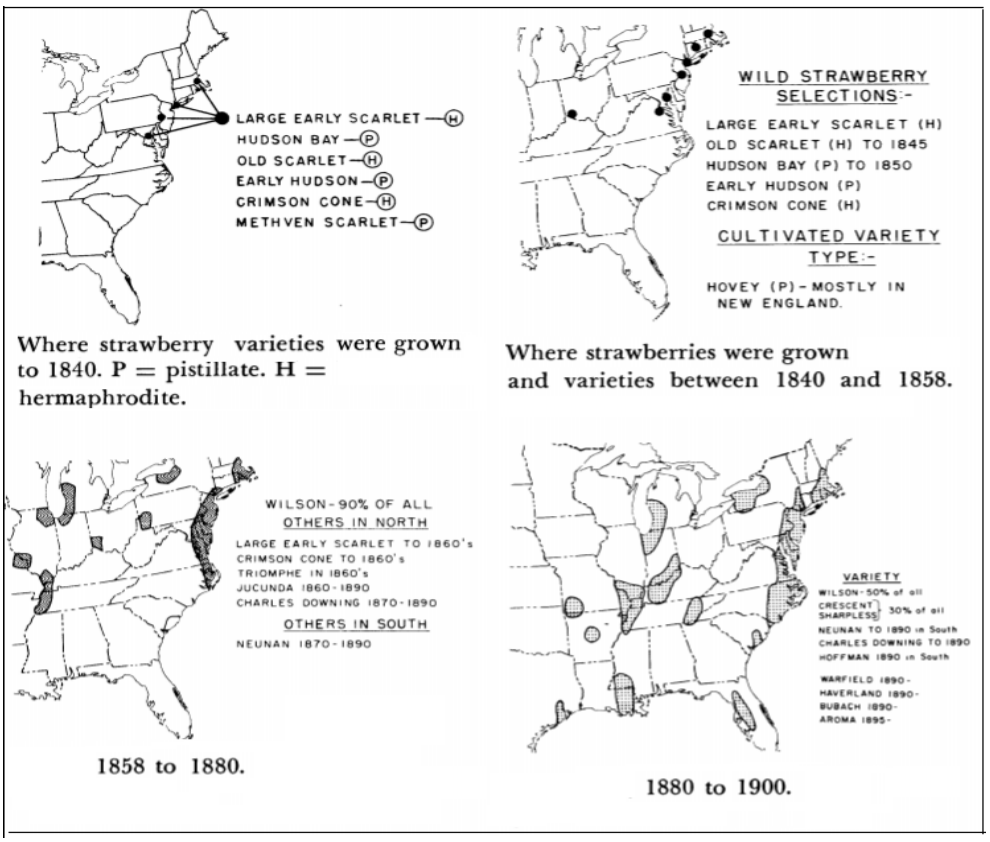
[13] Fuller, *The Illustrated Strawberry Culturist*, p. 10.

[14] Merrick JR., *The Strawberry and Its Culture*, p. 53.

[15] Fuller, *The Illustrated Strawberry Culturist*, pp. 7, 54.

agingly inconsistent. Cultivation techniques were copied almost wholesale from standard English practices, but were generally unsuitable for the North American climate.[16] In John Randolph's "*Treatise on Gardening*," one of the first American books to address strawberry cultivation, a section on the protection of strawberry beds during winter is conspicuously absent.[17] In addition, English practices had not yet addressed the mixing of different sexes, compounding climate issues with pollination deficiencies. Otherwise vigorous plants were often barren of fruit.[18] Personal gardens were primarily a hobby for wealthy amateurs who could afford both time and expense to care for these varieties without depending on them for income, and the berries they produced were for personal consumption or bartering with neighbors rather than for market. Garden culture was difficult and economically risky for the average farmer - the abundance of wild strawberries and the fickleness of domesticated ones limited its appeal.[19]

Figure 2.1: **Varieties under cultivation, 1800-1900.**



Source: Darrow, *The Strawberry*, 1966.

In Figure 2.1, we can see the movement of production through the 19th century: early

[16]Peacock, *Profits in Strawberry Production*, p. 7.
[17]Randolph, *A Treatise on Gardening*, p. 45.
[18]Fletcher, *The Strawberry in North America*, pp. 96–97.
[19]Ibid., pp. 6, 9, 43.

acreage in New England slowly progresses down the Atlantic Coast, with a single (though substantial) exception near Cincinnati. According to Fletcher, the trade in cultivated strawberries during the 18th century was vanishingly small; "perhaps the surplus product of some home gardens had been sold or bartered among neighbors, but only in a very limited way."[20] By the 19th century, American nurseries were beginning to import and propagate new, hardier cultivars from Europe; descended from Virginian stock, these strawberries were superior to their progenitors while still tolerant of the American climate. By 1812, enterprising farmers had established small strawberry operations near Boston, New York, Philadelphia, and Baltimore. George Darrow, horticulturist and leading expert on strawberry culture, believed these farmers were the first instance of commercial production in the US. Transportation and varietal improvement in the 1850s led to an initial geographic expansion, and towards the end of the 19th refrigeration would stretch these boundaries even further. We will expand upon a few of these key innovations in the following sections.

2.1 Proto-Commercial Production: 1800-1860s

American pomology entered its infancy in the early 19th century. For strawberries, there was no real delineation between commercial and personal cultivation, and many growers would participate in both simultaneously; with negligible capital and land requirements, the transition from gardening into for-profit production was largely a matter of scale and profit motive. Growers' early methods were an amalgam of pre-existing gardening techniques they had imported from England, experiential knowledge developed through trial and error, and a pervasive number of superstition. Strawberry production struggled with methodological contradictions that continued for decades; writers described this early period as a state of "horticultural chaos" and "great confusion."[21,22]

Cultivation could be enormously profitable under the right circumstances, but was stymied by an unclear path to success and the daunting challenge of shipping such a soft, perishable fruit to market. Average productivity was approximately 30-40 bushels to the acre,[23] and the industry remained under 1,500 acres nationally until the mid-1850s.[24] The first half of the 19th century served as a transitional, proto-commercial period for the strawberry industry, and in the interim Americans would continue to depend upon local foraging.[25] Over time, the American industry became increasingly self-contained, breaking away from imported European varieties and practices as American growers developed their own strawberry culture.[26] These efforts, along with the development of refrigeration and the prodigious construction of railroads, would culminate in a monumental industry boom following the introduction of the Wilson cultivar in the 1850s.[27]

[20] Fletcher, *The Strawberry in North America*, p. 12.

[21] Morris, "Tilton's Journal of Horticulture, Vol 6", p. 31.

[22] Peacock, *Profits in Strawberry Production*.

[23] 1 bushel = 32 quarts, so 960-1280 quarts. Currently, a quart is given as anywhere from 1.25 to 2.5lbs, so roughly 1 ton/acre. However, this range may be inaccurate given changes in berry size.

[24] Fletcher, *The Strawberry in North America*, pp. 33–34.

[25] Darrow, *The Strawberry*, p. 130.

[26] Bailey, "Cyclopedia of American Horticulture, Vol. 3", pp. 1399–1400.

[27] Peacock, *Profits in Strawberry Production*, pp. 5–6.

2.1.1 Production Characteristics

Commercial production was shaped by strawberries' fragility, perishable nature, and brief harvest season. Location was the most critical decision a farmer could make. Strawberries were only feasible to grow within a few miles' proximity to larger markets, as long distance shipments were essentially guaranteed to result in revenue loss from spoilage and possible additional damage from travel conditions. The inability to engage in interregional arbitrage also meant that production and demand shocks regularly led to severe market gluts or extreme scarcity. Marketing institutions were nonexistent; without the services of middlemen or wholesalers, farmers needed to sell fruit directly to their consumers. Location also dictated the availability of picking labor for harvest season. The demand for strawberry labor sharply increased during harvest, restricting the size of an individual operation - a single farmer, assuming they had assistance from family members, could manage no more than an acre or possibly two before needing to hire outside help. Labor became increasingly scarce the further a farm was from a town or city, reducing the amount of acreage that could be cultivated even as it became more affordable to do so.[28] More intensive land preparation, like a deeper agitation of the soil (known as tillage), reduced the feasible scale of production even further.[29] Local farmers were in unusually direct competition with one another as their markets overlapped both in location and in time. The strawberry season was comparatively early, and provided a farmer with income faster than other crops. However, as most growers were located in New England, the season was also extremely short - at most five weeks in mid-Spring. Farmers that shipped at the beginning of the season stood to profit tremendously, but this window of opportunity was measured in days, and a quart of strawberries would lose upwards of 80% of their market value before season was over.[30].

Production Practices

There were a few aspects of strawberry production that were common to the vast majority of strawberry growers. One of these was strawberry propagation; new plants were almost universally sourced from established "runners" - horizontal stems that extend outward from the plant - that eventually take root and develop into clones of the original. These are referred to as "mother" and "daughter" plants, the latter of which formed the initial planting stock of new strawberry operations. In future seasons, a farmer had the option of letting existing plants establish runners of their own. Propagation by seed was restricted to the breeding of new strawberries and to the select few varieties that did not produce runners. Another was the emphasis on moisture retention, achieved through some of soil type, mulching, and manure. Irrigation was sparingly adopted during the 19$^{\text{th}}$ century; drought was infrequent enough for most growers that the sizeable investment was difficult to justify, and was limited to land with either natural or artificial drainage.[31] Excessive irrigation, whether it was caused by human error or unanticipated rain, resulted in soft berries and could damage plants.[32]

[28] Fletcher, *The Strawberry in North America*, pp. 15, 68.
[29] Barry, "The Horticulturist, Vol. 3", pp. 395–396.
[30] Fletcher, *The Strawberry in North America*, pp. 15–16, 28.
[31] Hexamer, "The American Garden, Vol. 2, No. 2", p. 26.
[32] Fletcher, *Strawberry Growing*, pp. 80–82.

Instead, farmers relied on moisture retention - achieved by some of soil type, manure, and mulch - in order to prevent their strawberries from drying out.[33,34]

Before the division between gardening and commercial production became more distinct, many growers had adopted "hill" culture, an English-derived framework for cultivating strawberries that included methods of setting and caring for plants. Growers first created rectangular beds of tilled soil, which were usually mixed with large quantities of manure. Two or three parallel rows of strawberry plants were set out lengthwise within the bed, and each bed was separated by two to three-foot-wide "alleys" to provide paths for weeding, cultivating, and harvesting. Plants were set 18 to 24 inches apart within the rows to prevent crowding and facilitate picking along with the pruning of runners.[35,36,37] Pruning was partially for aesthetic purposes, but also increased yields, improved berry quality, and expedited harvesting. In some cases, a limited number of runners were allowed to take root in order to reduce the initial number of transplants.[38]

For strawberries, hill culture and its associated practices were horticultural orthodoxy, but as cultivation transitioned from a hobby of wealthy amateurs to a commercial endeavour, these guidelines competed with - and were eventually supplanted - by less intensive and more profit-oriented forms of culture. Removing extraneous runners demanded consistent, attentive labor, and was abandoned in many areas in favor of allowing strawberries to overrun the beds; this was referred to as "matted row" culture, after the matted appearance of the strawberry plants. This method reduced total labor expenditure, although the overall economic effect was ambiguous: more plants would yield larger crops, but the berries themselves tended to be smaller due to nutrient competition from overcrowding. Commercial growers in New Jersey rejected standard cultivation altogether, allowing their plants to fend for themselves.[39] Depending on price, fertilizer applications might be pared down or outright discarded.[40] Varieties were chosen to suit the less intensive methods of commercial production; the Redwood variety, for example, became popular specifically because it thrived even under indifferent care.[41]

Intensive cultivation methods, or "high" culture,[42] were more demanding but were not necessarily unprofitable. High-quality[43] varieties often sold for high prices but would fail to produce without substantial fertilization or under matted row conditions. The region around Boston became known for cultivating with deep, frequent tillage, heavy manure applications, and well-kept beds.[44] Although uncommon, some growers also adopted a particularly intensive technique known as "forcing" - manipulating plant fruiting patterns with heat in order to produce strawberries at different times of the year. Out-of-season strawberries commanded

[33] Worth, "The American Farmer, Vol. 5", p. 190.
[34] "Whippoorwill" (*pseudonym*), "The American Farmer, Vol. 6", p. 198.
[35] Hovey and P. H. Jr., "American Gardener's Magazine, Vol. 1", pp. 303–304.
[36] Worth, "The American Farmer, Vol. 5", p. 190.
[37] "Whippoorwill" (*pseudonym*), "The American Farmer, Vol. 6", p. 198.
[38] Fletcher, *The Strawberry in North America*, pp. 29, 43, 139.
[39] Ibid., pp. 15–16, 87–88.
[40] Richard, "The Horticulturist, Vol. 14", p. 369.
[41] B., "The American Farmer, Vol. 14", p. 278.
[42] I define "intensive culture" as greater levels of input/investment.
[43] A berry's quality was first determined by flavor, texture, and aroma; later, by size, firmness, and appearance.
[44] Fletcher, *The Strawberry in North America*, pp. 15–18, 26–34.

higher prices, but greenhouses were often too expensive to justify without other crops - one farmer stated strawberries were "considered as an extra crop... forced to fill up the vacancies on flues and other departments in cherry houses, vineries, etc."[45] As an economical, albeit laborious alternative, farmers forced their strawberries in "hot-beds," generating artificial heat with fire and decomposing manure.[46] Fruit production under a hot-bed system commenced anywhere from one to three weeks earlier than normal, and could be extremely profitable under the right circumstances, but appears to have been limited to small producers.[47]

2.1.2 Information Dissemination

Progress in strawberry cultivation was aided by newly established horticultural magazines, which filled a vital role in disseminating information to farmers prior to agricultural extension. Editors curated articles on gardening advice, prominent research, cultivar developments, and cultivation techniques, while gardeners made their own contributions through editorial correspondence, providing the community detailed reports of their own successes and failures in the field. Some publications, like the *Magazine of Horticulture*, provided a monthly set of directions to gardeners, indicating when they should begin undertaking certain agricultural work, while correspondents discussed their own horticultural experiments, debating the merits of different manures, planting times, and the value of extensive tillage. Unfortunately, these magazines were not immune from the horticultural confusion of the period; the science of pomology was not yet well defined, and its practitioners did not fundamentally understand the results of their experiments.[48] Magazines often published competing, sometimes confrontational sources of information, which were presented to a community that had not fully developed the tools to discriminate between them. Tillage, for example, was often recommended to improve water infiltration and retention of the soil, while accomplishing precisely the opposite. The breadth of the publication audience could exacerbate these issues, as growers would be offered advice that was incompatible with their local climate, soil, or market conditions. This confusion was perhaps best represented by a letter to the editor of *American Farmer*, in which a grower lamented that there was still no "systematic way of raising [strawberries] with success."[49]

Pre-Commercial Rotation Practices

Literature indicates a diversity of opinions regarding the importance of soil fertility and crop rotation. Some growers considered fertilization mandatory for production, particularly those that practiced intensive culture. Strawberries were thought to rapidly deplete the soil, and production of quality crops required intensive manuring.[50] Others believed rich soil was unnecessary or even injurious, encouraging the production of runners instead of fruit. They advocated walking a fine line between nutrient excess and scarcity, avoiding barnyard manure in favor of soil additives like ashes, potash, or vegetable compost; some might even

[45] "Agronome" (*pseudonym*), "The American Farmer, Vol. 14", p. 62.

[46] Sayers, "American Gardener's Magazine, Vol. 2", pp. 47–51.

[47] Fletcher, *The Strawberry in North America*, pp. 49–50.

[48] Bailey, "Cyclopedia of American Horticulture, Vol. 3", pp. 1398–1402.

[49] M., "The American Farmer, Vol. 5".

[50] "An Old Digger" (*pseudonym*), "The Horticulturist, Vol. 4", pp. 82–83.

intentionally deplete the soil by mixing in river sand.[51] The value of crop rotation was less ambiguous, but beliefs and practices still varied widely among growers. Some considered periodic relocation critical to maintaining crop value.[52] Strawberry beds were commonly torn up and replaced every two to three years, as yield and berry size were believed to decline the longer vines were in bearing.[53] Others viewed frequent bed renewal unnecessary or excessively labor intensive; still others believed that berry quality improved with the duration of a planting.[54] In the latter case, growers might continually replace old plants on a bed with fresh runners. This was frequently achieved by allowing runners to propagate in between the rows; when these were fully established, the original plants were plowed under. Under this method, a farmer could keep a single bed in production for several years, possibly over a decade.[55] Finally, there were also growers that were simply cavalier about the health of their soil. Some thought they could keep their strawberry beds intact indefinitely, or that their soil was somehow permanently inexhaustible.[56,57]

It is worth noting that pest pressure is conspicuously absent from early literature on strawberry cultivation, and only rarely discussed in horticultural magazines. Early growers that adopted crop rotation appear to have done so entirely for the purpose of maintaining soil fertility. This persisted well into the latter half of the 19th century; in the 1850s, Richard Pardee, author of one of the first comprehensive manuals of strawberry cultivation, went so far as to claim strawberries possessed a unique "exemption from all insect depredations."[58] This was not entirely true - grubs and aphids were known to attack strawberry plants - but the overall impact was considered trivial.

2.1.3 1830s-1840s: Transportation, the Hovey, and Pollination

Although the volume of commercial strawberry production during this period was still vanishingly small, household-level cultivation had spread throughout most of the United States. Cincinnati, situated between Pittsburgh and New Orleans on the Ohio river, had become the most economically important city in the developing Midwest; thanks to the efforts of its Horticultural Society - Nicholas Longworth in particular - it also became a center of strawberry excellence to rival Boston.[59] Three critical reliability issues needed to be addressed for commercial strawberry production to become feasible on a meaningful scale - plant survival, consistency in bearing, and fruit condition after shipment.

Inadequate transportation remained an impediment to strawberry cultivation through the 1840s. Shipments of agricultural produce were restricted to either wagons or, when available, local waterways. Unfortunately, these methods were neither timely nor efficient, and urban centers were dependent on local production for perishable goods. Land transport

[51] R. Pardee, *A Complete Manual*, pp. 17–18, 105–106.
[52] "An Old Digger" (*pseudonym*), "The Horticulturist, Vol. 4", pp. 82–83.
[53] Kenrick, *The New American Orchardist*, pp. 305–306.
[54] R. Pardee, *A Complete Manual*, pp. 28–29.
[55] "Whippoorwill" (*pseudonym*), "The American Farmer, Vol. 6", p. 198.
[56] Gibbes, "The American Farmer, Vol. 5", p. 124.
[57] L. Allen, "The Cultivator", pp. 38–39.
[58] R. Pardee, *A Complete Manual*, p. 121.
[59] Berry, *Western Prices Before 1861*, pp. 6–7.

could take days to travel a few dozen miles, and roads outside of the New York/Pennsylvania region were usually in poor condition. Farmers could ship longer distances via water, often cultivating land where they could float rafts laden with produce downstream; however, craft were typically broken up into lumber at the end of the journey, as it was too difficult to navigate them back upstream. These methods were only economically feasible for high-value goods, and made it nearly impossible for farmers to dispose of surplus production. Commercial interests lobbied for transportation infrastructure following the War of 1812, resulting in a flurry of new construction - first of turnpikes, then of canals. The turnpikes were a striking improvement over existing roads, but were expensive to maintain and quickly fell into disrepair; levied tolls additionally discouraged long-distance freight. Water allowed conveyance of greater weight at faster speeds, but the meandering routes added significant time to the journey. Canals provided direct routes between markets, and the success of the Erie Canal inspired state governments to undertake thousands of miles of canal construction regardless of the expense. Developments in steam locomotion were also re-purposed from passenger transportation to freight, and by the 1830s steamboats had become responsible for moving increasing amounts of agricultural produce.[60] There were several limitations on water as a mode of transportation, not the least of which was their dependence on water; drought or freezing temperatures restricted travel. In addition, unventilated cargo storage accelerated the spoilage of fruit as temperatures climbed belowdeck.[61]. Still, these developments successfully relaxed constraints on short distance shipments of perishable goods, strawberries included. The Chesapeake-Delaware Canal, completed in 1829, allowed Baltimore to send surplus production to Philadelphia by the early 1830s.[62] Growers in Norfolk, Virginia shipped small quantities to New York, Baltimore, and Philadelphia; although they often reached the market in poor condition, they were also the first to arrive, and were sold for high prices.[63]

Another impediment to commercial production - and cultivation in general - was the absence of domestic strawberry breeding. American growers depended on England, Belgium, and France for the introduction of new cultivars, but European strawberries were ill-suited for American cultivation; despite their larger size and excellent flavor, their intolerance of the climatic differences limited their viability.[64,65] Convinced that they "must look to our own gardens for *hardy* varieties of strawberries," American horticulturists began raising an ever greater number of varieties to improve upon the Virginian.[66] The "Hovey" strawberry in 1838 - named after its originator, Charles Hovey - was the first breakthrough success. Hovey's strawberry was large-fruited, well-flavored, and comparatively hardy, and the first commercially successful cultivar produced in the United States; its introduction created an uproar in the horticultural community. Stephen Wilhelm and James Sagen believed this to be the catalyst for further development:

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[60] G. R. Taylor, "The Transportation Revolution", pp. 18–38, 56–60.
[61] McCorkle, "Moving Perishables to Market", pp. 47–49.
[62] G. Smith, "The American Farmer, Vol. 14", p. 49.
[63] Fletcher, *The Strawberry in North America*, pp. 66–67.
[64] Morris, "Tilton's Journal of Horticulture, Vol 6", p. 28.
[65] Darrow, *The Strawberry*, p. 130.
[66] Hovey, "Magazine of Horticulture, Vol. 3", pp. 242–246.

> "The single major impulse given both strawberry culture and strawberry hybridization in the United States was the development of Hovey's Seedling... for years it was the standard of market excellence, and almost the perfect strawberry."[67]

Unfortunately, the Hovey also demanded attentive care and extensive fertilizing, and, as a pistillate, was unproductive without pollination, making yields appear to be somewhat erratic. A quart of Hovey strawberries could sell at double the price of other varieties, but Virginian-derived cultivars would continue to account for almost all strawberry acreage.[68] Despite the extraordinary horticultural excitement it generated, Boston, as both the origin of the Hovey and a region known for high culture, was the only area to demonstrate appreciable commercial interest.[69] Regardless, the Hovey represented an important milestone in American cultivation, and its outstanding quality - along with the financial success of Hovey himself - invigorated new American breeding efforts.[70] The end result was an industry newly independent from European cultivars - less than 10 years after the Hovey's introduction, the Boston strawberry market was almost entirely supplied with American varieties.[71]

The Hovey's economic potential also brought the importance of pollination to the forefront of strawberry horticulture. By the 1820s, some farmers had already become cognizant of strawberries' potential dimorphism, and they had begun experimenting with different ratios of staminate and pistillate plants.[72] Other growers considered this "popular error" - barren plants simply possessed abortive flowers that were incapable of producing fruit.[73] Commercial production had exacerbated crop failures from pollination deficiency; by attempting to maximize fruit size and productivity, farmers had over-selected pistillate cultivars, creating the same pollination issues European breeders had accidentally stumbled upon a century prior. Garden culture had placed less emphasis on selectivity, often growing multiple cultivars in the same field and unknowingly mitigating some of these potential losses. The same held true for nurseries, with consequences for their customers - a cultivar's productivity in a nursery was not necessarily a reflection of its performance on a farm.[74]

Nicholas Longworth, a Cincinnati horticulturist, had become fully convinced of the dioecious nature of strawberries, and discussed his findings in an article to the *Magazine of Horticulture* in 1834. Shortly afterwards, Longworth would also identify the Hovey strawberry as a pistillate variety; this brought him into direct conflict with the horticulturist Hovey himself, also the editor of the magazine.[75] Hovey and his correspondents vehemently rejected the pistillate designation and would do so for many years; in March of 1836, Hovey's magazine included an article claiming that the theory of sexual dimorphism, having been discarded by English horticulturists, was now "exploded."[76] This dispute grew to encompass

[67] S. Wilhelm and James Sagen, *A History of the Strawberry*, p. 149.
[68] Darrow, *The Strawberry*, pp. 130–133.
[69] S. Wilhelm and James Sagen, *A History of the Strawberry*, pp. 150–151.
[70] R. Pardee, *A Complete Manual*, p. 43.
[71] Hovey, "Magazine of Horticulture, Vol. 11", pp. 290–294.
[72] Worth, "The American Farmer, Vol. 5", p. 191.
[73] Anonymous, "The American Farmer, Vol. 14", p. 273.
[74] Fletcher, *The Strawberry in North America*, pp. 97–98.
[75] Ibid., pp. 99–105.
[76] Vose, "American Gardener's Magazine, Vol. 2", p. 90.

other publications as well as regional horticultural societies, and would eventually acquire the moniker of "the strawberry question." The question itself lasted longer than Hovey's objections - by 1845, he had begrudgingly accepted that "defective" plants may not produce as abundantly without "perfect" ones nearby.[77] Longworth surmised that Hovey's eventual concession was financial in nature, related to the recent introduction of his new strawberry, the Boston Pine, which Hovey claimed could be grown with the Hovey cultivar as a pollinator.[78]

Opposition to Longworth's strawberry theory persisted until the latter half of the 1850s. Longworth himself made numerous attempts to convince his horticultural peers, including public challenges and associated monetary awards to anyone who could disprove his theory.[79] Other horticulturists would continue to debate his findings, but given the observable effects on yields it appeared that the question was all but resolved for commercial growers.[80] Cincinnati strawberries had sold for 25 to 50 cents per quart before the adoption of pistillate/staminate mixing; by the 1840s, they were just 5 to 10 cents, less than half the price of a quart on the Boston market. In 1847, the editor of *The Horticulturist* wrote:

> "That the market of Cincinnati was last year supplied with... the largest and cheapest supply known in any city in the world, is the best evidence of the extraordinary result of their mode of rejecting all but the pistillate sorts - with a small admixture of staminates to fertilize them."[81]

Three years later, a nurseryman echoed a similar sentiment:

> "Why is it that much larger quantities of the strawberry are grown at Cincinnati, than at any other place in the United States? Is it owing to some peculiarity in the soil or climate, or both combined? Or is it to be attributed to the better mode of culture there? It is said that a full crop is gathered from year to year; and that hundreds of bushels may be seen in the market at once."[82]

As empirical evidence multiplied, public criticism of Longworth's theory grew increasingly esoteric and divorced from concerns material to growers, to the point where, in 1857, the editor of *The Horticulturist* decided to cease publication of any further discussion.[83] By the end of the decade, the strawberry "question" was considered definitively answered by both farmers and the larger horticultural community.[84]

2.1.4 1850s-1860s: Railroads and the Wilson

The scale of commercial cultivation had expanded slightly thanks to the Hovey, and its geographical spread had increased with the shifts in American population distribution and new

[77] Hovey, "Magazine of Horticulture, Vol. 11", p. 4.
[78] N. Longworth, "The Horticulturist, Vol. 2", p. 146.
[79] Prince, "The Horticulturist, Vol. 2", p. 572.
[80] Meehan, "The Horticulturist, Vol. 3", p. 366.
[81] N. Longworth, "The Horticulturist, Vol. 2", p. 25.
[82] Hodge, "The Horticulturist, Vol. 5", p. 149.
[83] Nicholas Longworth and Meehan, "The Horticulturist, Vol. 7", p. 518.
[84] R. Pardee, *A Complete Manual*, p. 7.

transportation technology. Southern cultivation was potentially very profitable; although the climate required hardier varieties, the bearing season was both earlier and substantially longer than in the north; Where the Boston or New York season lasted for two to three weeks, Georgia growers could harvest berries between four to five months.[85,86] Annapolis had become another major center of commercial strawberry culture, reaching 600 acres - 40% of the estimated national total - and producing slightly less than 1,100 quarts to the acre.[87] Further south, Charleston growers reportedly produced an impressive 3,200 quarts to the acre, more than three times the average yield in Cincinnati.[88] Cultivation in California was similarly promising. Like the southern states, farmers exchanged higher water demands for greater yields and a longer bearing season, but California's mild climate was also well-suited for growing the large-fruited, less hardy varieties descended from the Chilean.[89] Neither region, however, could immediately capitalize on these advantages. The largest markets at the time - New York, Baltimore, Philadelphia - were inaccessible without faster modes of transportation.

The construction boom of railroads in the 1840s and 1850s presented growers with the first truly viable method for long-distance shipments. The early system had several flaws: it was more expensive than water freight, poor suspension on trains caused physical damage to strawberries, and high levels of independent ownership reduced cohesiveness of the rail network and led to delays. But it also held significant promise - rail was 50 to 100 percent faster than steamboat, ran routes more direct than either rivers or canals, and could operate year-round without regard to the weather.[90] Shipment speed was a perpetual concern, and express companies made arrangements with rail lines to attach their cars to fast freight or passenger trains, allowing them to reach markets a day ahead of other schedules in exchange for the express company taking responsibility for scheduling and loading. The rail lines themselves also hauled fruit in ventilator cars, built to provide better internal air circulation to mitigate the buildup of heat.[91] Both Ohio and Maryland growers could ship railcars of strawberries to New York City by the 1860s; John Knox, a famous grower in Pittsburgh, was known to send strawberries to markets 400 miles away. By the 1880s, New York markets were receiving strawberries from as far as Central Florida.[92] Ice was used to refrigerate railcars of strawberries for the first time in 1843, but early attempts were disappointing failures. Growers' misgivings about refrigeration lasted until Parker Earle's successful experiments with fruit precooling and new refrigerator cars in the 1860s and 1870s. By the 20$^{\text{th}}$ century, companies providing refrigeration services had been established, and had begun shipping perishable goods to markets hundreds of miles distant.[93]

The Wilson cultivar, introduced in 1854, capitalized on the ongoing evolution of the transportation network to an incredible degree. The plant itself was robust enough to be

[85] W. W. White, "The Horticulturist, Vol. 3", pp. 409–410.
[86] Jacques, "The American Farmer, Vol. 1", p. 74.
[87] J. J. Smith, "The Horticulturist, Vol. 7", pp. 388–389.
[88] A. Downing, "The Horticulturist, Vol. 3", p. 351.
[89] S. Wilhelm and James Sagen, *A History of the Strawberry*, pp. 164–171.
[90] G. R. Taylor, "The Transportation Revolution", pp. 71–86.
[91] McCorkle, "Moving Perishables to Market", pp. 55–57.
[92] Fletcher, *The Strawberry in North America*, pp. 46–55.
[93] Earle, *Development of the Trucking Interests*, pp. 444–446.

grown in a range of climates and on almost any soil type, enabling cultivation to develop in any region with access to rail. It was productive and reliably so - it produced minimal runners, so production was not substantially affected if growers neglected to prune them. It also produced large, attractive fruit that sold exceedingly well - unlike other large strawberries, the Wilson was also extremely firm, preventing damage during long-distance shipping and preserving its appearance when it arrived at market.[94] Perhaps most importantly, the Wilson was also the first hermaphroditic cultivar to combine so many of these traits. Longworth's theory had overcome one of the major hurdles to commercial production, but the primary beneficiaries were amateur gardeners or those who could afford professional horticultural services. The Wilson's ability to self-pollinate simplified cultivation, opening up the strawberry market to growers that had never been able to participate; the subsequent strawberry "fever" brought fruit within reach of those who had rarely been able to afford it. The Wilson was uncontested in its importance in the strawberry industry for the next two decades, and would comprise the overwhelming majority of all acreage until the 1880s.[95]

[94]Darrow, *The Strawberry*, p. 134.

[95]Fletcher, *The Strawberry in North America*, pp. 35–43.

Chapter 3

Strawberry Commercialization

The Wilson and the spread of rail signified the conclusion of the proto-commercial period of the strawberry industry and the beginning of an unprecedented nationwide expansion, with production reaching 150,000 acres in less than 50 years. By the end of the century, the diet of a growing urban population began to incorporate greater amounts of vegetables and fruit - strawberries included - leading to a substantial expansion in truck[1] crop production.[2] Cultural techniques would continue to evolve. One in particular - the removal of flowers in the first year - appears to have become common sometime in the mid to late 18th century, based on its presence in cultivation manuals. The purpose was similar to pruning runners; by preventing strawberries from fruiting before the roots became established, the plant itself was more vigorous and the second-year yields were larger.[3,4,5] Breeders continued to introduce an ever-increasing number of new, desirable varieties, although they would not wrest market control away from the Wilson for many years. The supply chain had taken on additional levels of complexity, as longer distances and higher production volumes made it infeasible for most strawberry farmers to sell their own produce. Farmers began making arrangements with city commission houses or agents to market their produce for them in exchange for a percentage of the sales. A day's harvest was shipped to the commission houses overnight in small boxes nested in large wooden crates and sold to grocers and restaurateurs well before sunrise. A farmer's income was at the mercy of the commission merchant, depending on their performance as well as their honesty.[6]

The expansion of strawberry production was widely considered a societal good - the American Pomological Society believed it was the first step towards making fruit regularly available to all classes of society,[7] and the Rural Club of New York boasted that now "even the poorest child can get a dish of strawberries."[8] Yet there were also concerns regarding the cultural ramifications of commercial production, including the emphasis of quantity to the exclusion of quality.[9] Market growers were criticized for "looking upon [the strawberry's]

[1] "Truck" crops are valuable fruit/vegetable crops (excluding orchards) grown on a large scale and transported.

[2] McCorkle, "Moving Perishables to Market", pp. 42–45.

[3] R. Pardee, *A Complete Manual*.

[4] Crawford, *Crawford's Strawberry Culture with Catalogue*, p. 5.

[5] Snider, *How to Raise a Large Crop of Strawberries*, pp. 14–15.

[6] Earle, *Development of the Trucking Interests*, pp. 447–448.

[7] Not Listed, "California Horticulturist, Vol. 1", p. 340.

[8] Williams, "The Horticulturist, Vol. 26", p. 264.

[9] Williams, "The Horticulturist, Vol. 24", p. 230.

culture entirely with reference to profit,"[10], supplying the market with small, dirty berries and creating a strawberry culture of "miserably low condition."[11] Although the hardy, productive Wilson had become "the people's berry," it was infamous for its sour and acidic flavor.[12] Its productivity under neglect also relaxed horticultural standards. The Wilson produced only a moderate amount of runners and continued to bear even in overcrowded conditions, leading growers to replace matted row culture with even less intensive method that Fletcher referred to as "broadcast training." Under this style of cultivation, plant spacing was discarded in favor of allowing strawberry vines to fill an entire plot, while fertilization, tillage, and weeding were all either minimized or abandoned.[13]

Aside from horticulturists' general disapproval of this form of extensive cultivation, they also considered it to be self-sabotaging; commercial growers were increasing overall yields and reducing costs, but faced a disproportionate reduction in price. The Ohio Pomological Society believed "the greater produce of the modern methods," would eventually displace "primitive" low intensity operations.[14] Consumer preferences were also indicted; in 1862, Hovey opined that "the *public taste* was no taste at all, size and cheapness carried the day in the public market."[15] A member of the Rural Club stated that "in the New York market strawberries are not bought for their flavor, but for their looks."[16] Some organizations, like the American Pomological Society or the Massachusetts Horticultural Society, believed it necessary to establish standards for "the proper characteristics of a strawberry,"[17] concerned that profitable but inferior varieties grown had "usurped" the market.[18]

Market production was supported by seemingly insatiable demand from large Eastern cities and high prices resulting from Civil War scarcity. Growth was particularly in the Mid-Atlantic, with Maryland, Delaware, and New Jersey well situated to supply both New York City and Philadelphia.[19,20] Exports from New Jersey became so overwhelming to local New York growers that they altered their production schedules in order to avoid direct competition. However, the illusion of ever-increasing demand was broken by the Mid-Atlantic's disastrous market seasons in the late 1860s and early 1870s. A vast amount of strawberries sold for prices barely high enough to cover the expense of picking, and in extreme cases they were simply abandoned to rot on the vine. New Jersey growers sent their berries to market latest and appear to have been the most severely impacted as a result.[21] In 1865, returns for an average strawberry grower in southern New Jersey were roughly \$200 per acre;[22] by 1869, this figure was closer to \$100, half of which was consumed by expenses.[23]

[10] Not Listed, "The Horticulturist, Vol. 19", p. 229.
[11] Barry, "The Horticulturist, Vol. 3", p. 396.
[12] Elliott, "The Horticulturist, Vol. 23", p. 237.
[13] Fletcher, *The Strawberry in North America*, pp. 87–89.
[14] Society, *Ohio State Board of Agriculture, Report No. 19*, p. 54.
[15] Hovey, "Magazine of Horticulture, Vol. 29", p. 334.
[16] Williams, "The Horticulturist, Vol. 26", p. 260.
[17] Hovey, "Magazine of Horticulture, Vol. 27", pp. 482–487.
[18] Hovey, "Magazine of Horticulture, Vol. 30", p. 248.
[19] Williams, "The Horticulturist, Vol. 24", p. 324.
[20] Fletcher, *The Strawberry in North America*, pp. 60–62.
[21] Williams, "The Horticulturist, Vol. 23", pp. 238–239.
[22] N., "The Horticulturist, Vol. 20", p. 150.
[23] Rolliffe, "The Horticulturist, Vol. 24", p. 237.

The challenges the strawberry industry was experiencing were and are still typical of agricultural production; balancing supply and demand in conditions of uncertainty from market conditions and weather patterns. The Rural Club of New York, among many others, claimed that the cause of the market downturn was not overproduction, but growers' inferior produce - whether by poor cultivation or spoilage in transit. They believed demand for larger berries was still unsated, and that if provided with higher quality shipments, commissioners could sell even greater quantities without difficulty. This may be somewhat specious; the downturn was noted as having affected both high and low quality fruit,[24] and records from New York commission merchants in 1871 show that prices of the Wilson and a higher-quality cultivar were closely correlated.[25] However, more contemporary literature supports the Rural Club's argument, suggesting that product differentiation along quality characteristics and coordination may present potential solutions to depressed prices from overproduction.[26] Regardless, economic losses disproportionately fell on extensive growers, and highlighted the need for improvements in cultivation as well as the supply chain.

3.1 A New Strawberry Supply Chain

The relationship between production volume and poor market seasons notwithstanding, it was clear that the capacity of the existing supply chain was under appreciable strain. Strawberries were still extremely time sensitive; overstocked markets or delays in shipments compelled commissioners to drastically reduce prices, or in some cases destroy their remaining produce.[27] There exist numerous reports of excess strawberries being disposed of, either dumped into nearby waterways or fed to animals.[28] The upstream supply chain was also experiencing its own growing pains related to geographic expansion. Greater distances made informal agreements between nurseries and growers more difficult to enforce, and persistent issues with consumer deception had developed in response.

Many developments in the strawberry supply chain were also associated to the spatial concentration of production, with various external economies of scale creating a positive feedback loop in larger shipping districts. In order to attract railroads to an area, farmers had to convince them it was worth the investment, i.e., traffic was sufficient to justify the provision of shipping services.[29] Once these services were established, the number of farmers - and therefore, production - influenced the quality of these services, including shipping schedules and related facilities. High production density increased the likelihood of inter-railroad competition, which factored into rate reductions and better quality of services, while also making it easier for associations to reduce transportation costs through shipment consolidation. High production volume could attract buyers to the shipping origin rather than the destination; under these circumstances, farmers were paid free on board rather than on consignment, avoiding the risks associated with transportation and marketing.[30] Below,

[24]Williams, "The Horticulturist, Vol. 23", p. 238.

[25]C. Downing, "The Horticulturist, Vol. 26", p. 265.

[26]Cochrane, *The Development of American Agriculture: A Historical Analysis.*

[27]Williams, "The Horticulturist, Vol. 26", p. 226.

[28]Hollister, "The American Garden, Vol. 12, No. 2", p. 71.

[29]McCorkle, "Southern Truck Growers' Associations", p. 89.

[30]Fletcher, *Strawberry Growing*, pp. 3–6.

we will examine some of these related issues in more detail.

Cultivars and Marketing: Risk in the upstream supply chain - sourcing plants - appears to have been mitigated by relationships within the horticultural community. We observe that horticultural magazines frequently became arbiters of professional behavior. Nurseries' reputations, for example, were an informal means of risk reduction for growers, and editors of magazines might vouch for their reliability or call on them to reimburse their customers if the nursery had made an error or delivered an inferior product. Over time, as cultivation extended into different climates, regionally-adapted cultivars became more difficult to acquire from existing, reputable establishments. Unfortunately, local nurseries took several years to establish, were slow to develop dependable patronage, and often found it financially difficult to distribute their plants. Larger nurseries back east sent their own sales representatives westward, but farmers had to distinguish between genuine nursery agents and swindlers peddling fraudulent goods. Speculation for new, potentially profitable cultivars was also rampant. John Knox, an enormously successful Pittsburgh grower, propagated his stock of unknown heritage and sold it for exorbitantly high prices, only for other farmers to discover it was an existing, previously discarded variety.[31] Peddlers often took advantage of this demand by selling old varieties under false pretenses,[32] but even if their descriptions were accurate, strawberries that were prolific in one region of the U.S. were often poorly adapted for other localities.[33] Some nurseries collaborated with these peddlers as it allowed them to move their older, undesirable stock.[34] For a farmer to prove that they had been cheated, they typically had to bring the strawberry plant to fruition - a berry could be used to identify a cultivar, but a dead transplant was easily attributed to poor weather or farmer error.

Production Variation: The nature of the strawberry - a multi-year, distance-sensitive crop with diminishing yields - created unusual cyclic effects in production both within and across seasons. Market availability was not continuous, but would occur in waves; for most producers, the strawberry season was still only two to four weeks long, and incoming carloads for a city market would wax and wane as different production regions hit their annual peak. This pattern was amplified by the incentive of high early-season prices - or perhaps more accurately, the inability to profit from late production - as well as the relative lack of competition from other fruits earlier in the year. At their peak, strawberry shipments could reach four times their seasonal average in a single day.

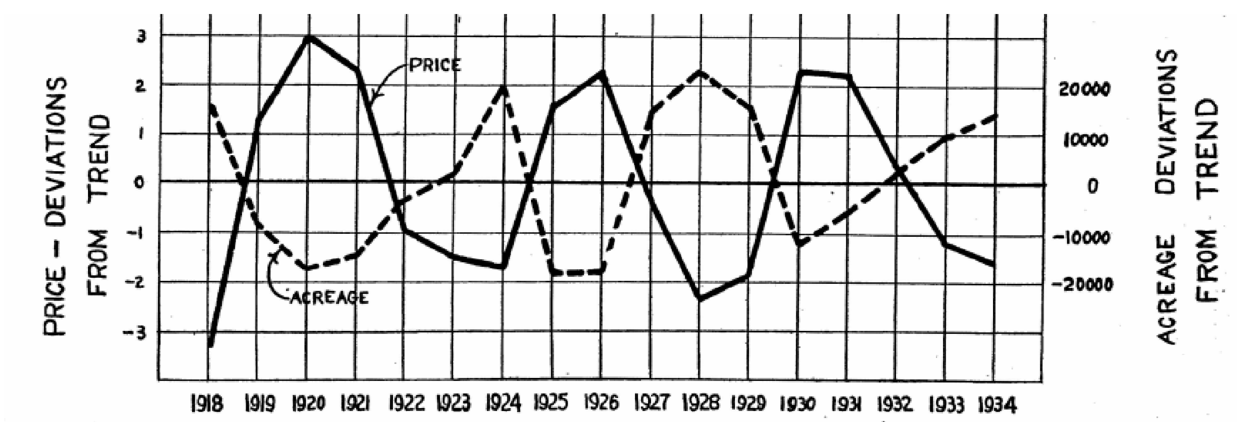
Aside from causing undesirable price depressions, these cycles had physical ramifications for the supply chain. Periods of high production caused noticeable strain on the rail system, sufficient to tax the capacity of the rail system and its loaders, and train delays and subsequent loss of revenue became more frequent.[35] The commission system was extremely sensitive to even short interruptions; retailers became impatient if a train failed to arrive on time, and both prices and sales would rapidly decrease. In 1871, a shipment of 256,000 quarts of strawberries was an hour late to New York City, resulting in an aggregate loss of $15,000 to

[31] Fletcher, *The Strawberry in North America*, pp. 48–49.
[32] Reynolds, "The Horticulturist, Vol. 24", p. 204.
[33] Saul, "The Horticulturist, Vol. 6", pp. 550–551.
[34] Hayter, "Horticultural Humbuggery", pp. 207–214, 221.
[35] Williams, "The Horticulturist, Vol. 26", pp. 262–263.

the growers. Assuming prices ranging from 20 to 30 cents per quart, this delay amounted to at least 20 percent of the shipment's total value. Delays were a weekly occurrence during seasonal peaks, and represented a significant loss to the strawberry industry.[36] Growers were advised to "not mass together at any given point," stabilizing supply by spreading out the season; however, for rail shipments to be efficient, they also required geographically concentrated production.[37]

Strawberry cultivation also exhibited a cyclic relationship between acreage and price, which can be seen in Figure 3.1:

Figure 3.1: **Price and Acreage Cycles in the US.**



Source: Thomsen, *Factors Affecting Strawberry Prices*, 1935

As with other commodities, growers entered or exited production based on prevailing strawberry prices, but the initial fixed cost of establishment and the potential for multiple years of production caused a lag in supply response as prices adjusted.[38,39] In Figure 3.1, we see that this lagged response created an ongoing oscillation between prices and acreage, a phenomenon later formalized by Mordecai Ezekiel in his "Cobweb Theorem" of production.[40] Since this initial paper, the basic cobweb model has since been generalized to account for a wider array of conditions, including multiple commodities or variations in period frequency.[41,42] Recent literature has also attempted to incorporate cobweb models with those of inventory management; Mitra and Boussard (2012), for example, found that a lack of inter-annual storage was associated with periodic price series in commodities.[43]

Capital attrition: The integration of railroads and commission houses into the strawberry supply chain also necessitated methods of preserving fruit condition in transit and facilitating

[36] Williams, "The Horticulturist, Vol. 26", pp. 262–263.
[37] Rolliffe, "The Horticulturist, Vol. 24", p. 239.
[38] Goble, *Tennessee's Competitive Position*, pp. 20–21.
[39] F. Thomsen, *Factors Affecting Strawberry Price*, pp. 3–6.
[40] Ezekiel, "The Cobweb Theorem".
[41] Waugh, "Cobweb Models".
[42] Talpaz, "Multi-Frequency Cobweb Model".
[43] Mitra and Boussard, "Agricultural Commodity Price Fluctuations with Storage".

distribution. Wooden chests and boxes became commonplace - multiple small boxes, filled by pickers over the course of a day, would be placed into larger wooden chests labeled with the name of the commission agent recipient. Well-crafted chests were sturdy but expensive, and maintaining their appearance was part of a farmer's marketing effort, as the condition of the chests influenced buyers and reflected on the quality of a grower.[44] In theory, chests sent out with strawberry shipments would be returned to a grower by a shipping agent within a few days of sale, and a deposit was requested to ensure this was the case. In practice, speculative buyers would ship to distant markets, occupying the chests for weeks; they were regularly damaged during transit and often returned to the wrong grower. Return service became increasingly less feasible as the volume of production grew, and was eventually discarded in favor of what were known as "gift" packages or crates, flimsier but cheaper containers intended to be kept by the consumer.[45,46]

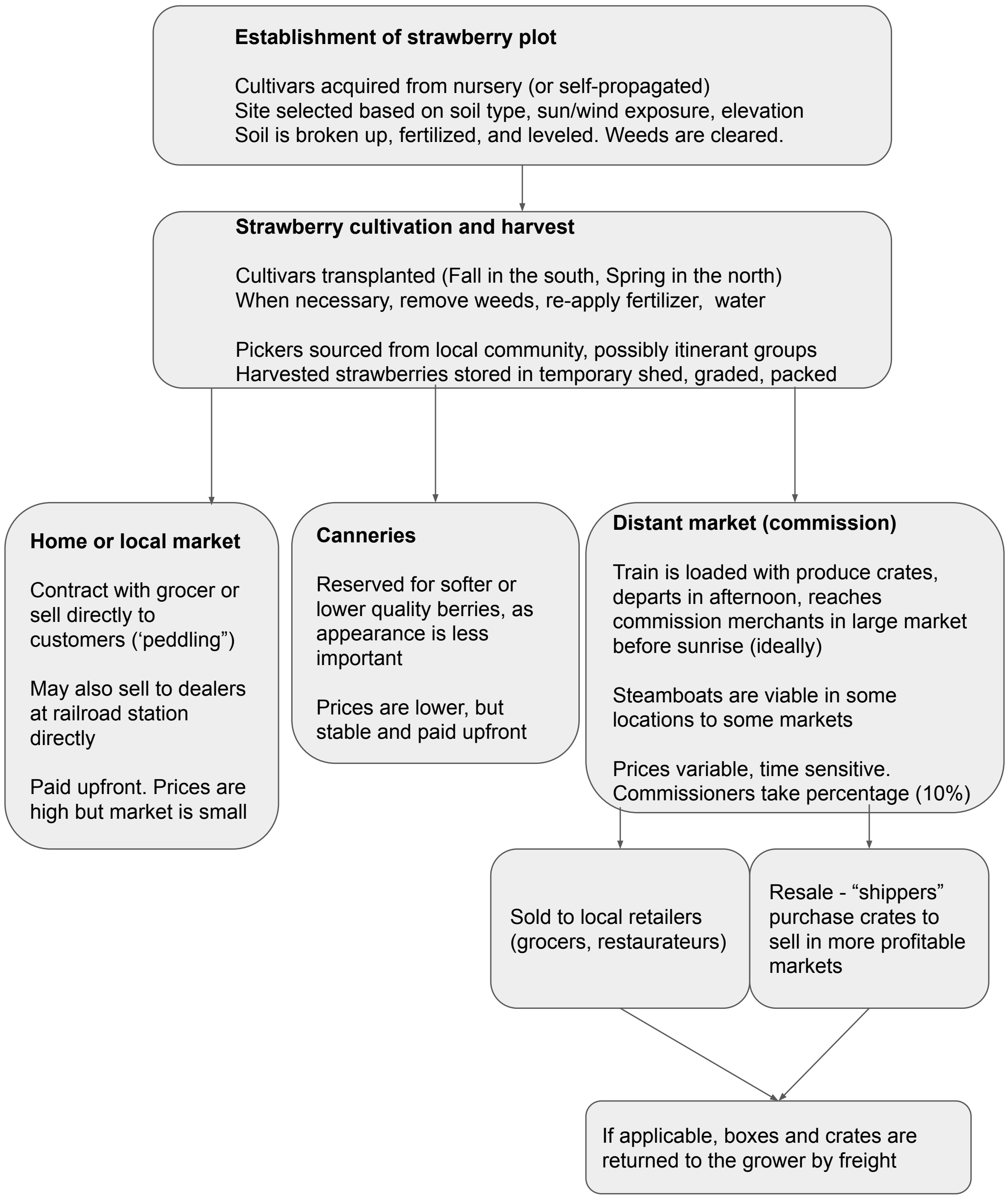
Standardization: The effects of supply chain irregularities were more pronounced as the chain itself became longer. Non-standard containers and labels, for example, reduced consumers' willingness to pay, while unusually-shaped strawberries were more easily bruised over long distances and required more time for hulling.[47][48,49] While not specific to the strawberry supply chain itself, railroads had inherent structural delays due to the organization of their construction which impacted the distances strawberries could be shipped. During the railroad boom in the mid-19th century, there were certain "standard gauges"[50] that were adopted, but no actual obligation for companies to adhere to them. As a result, the rail network was fragmented by a proliferation of gauges at regional, state, and intrastate levels. This was particularly disruptive between the North and South, where different standards had been adopted. At each disjoint in the track, the wheel connections of the railcar, or trucks, needed to be switched out, requiring both time and costly equipment and impeding traffic of perishable goods.[51]

Fruit condition and profits: A major component of time sensitivity was the lack of refrigeration and cold storage. Early ventilator cars were rudimentary and designed solely for facilitating air circulation, and strawberries might spend a full 48 hours in transit before arriving at a market. Spoilage was further compounded by damage caused by railcars' poor suspension.[52] Distance from a market was therefore a double-edged sword. Growers had a short window of opportunity in which they could make a considerable profit; after the local strawberry season began they would be forced to compete against produce that was a day fresher than their own.

Figure 3.2 describes an abbreviated strawberry supply chain during the late 19th century from planting to consumption.

[44] Williams, "The Horticulturist, Vol. 24", p. 229.
[45] Morris, "Tilton's Journal of Horticulture, Vol 6", pp. 288–290.
[46] Fletcher, *The Strawberry in North America*, pp. 83–86.
[47] Hulling is the removal of the strawberry calyx, or the green stem of the berry.
[48] S. Wilhelm and James Sagen, *A History of the Strawberry*, p. 210.
[49] Fletcher, *The Strawberry in North America*, pp. 166–168.
[50] Spacing between the rails of the track.
[51] A. Taylor, "Nematocides and Nematicides - A History", pp. 82–83.
[52] Fletcher, *Strawberry Growing*, pp. 187–188.

Figure 3.2: **Strawberry production and marketing, late 1800s.**



Establishment, cultivation, and harvest descriptions are drawn from what were considered best practices for a typical grower, although, as previously discussed, deviations were extremely common.

3.2 Adaptations in the Supply Chain

Farmers sought to improve their economic outcomes through technical innovation or cultural changes to the existing strawberry supply chain. Some of these were intended to directly increase sale prices, while others were designed to mitigate risk, either blunting the impact of supply chain disruptions or avoiding them entirely. The primary concern for long distance growers was the market condition of their fruit, as damage would render their produce nearly impossible to sell. One partially successful strategy was to ship berries before they fully ripened; ideally, they were firm enough to resist shipping damage, but would ripen adequately by the time they reached the market. Farmers also avoided high temperatures by picking in the early morning; berries were then stored in boxes kept in a temporary shed.[53] By avoiding sun exposure and reducing temperatures in the shade, farmers could somewhat reduce post-harvest ripening and potential spoilage. However, unripe berries were also undesirable, and growers walked a fine line between picking too early or too late.[54] Lacking alternatives, farmers also began adopting risk-mitigation strategies. The geographical expansion that had followed the development of rail had been somewhat overambitious, and farmers began shifting production back towards their target markets to reduce the impact of train inconsistency.[55] Alternatives to selling produce wholesale in large cities also became increasingly attractive; local markets were smaller, but could be highly lucrative if local production was not yet established. This was not feasible for every grower, but fruit and vegetable canneries were also seen as a potential avenue for diverting "second-class" berries,[56] and had the additional benefit of paying the farmer on delivery of their fruit without the associated risk of the fresh market.[57] Diversification into raspberries and blackberries was also an option; farmers could theoretically take advantage of the later ripening seasons and the overlap in capital and cultivation methods, although how many chose to do so is unclear.[58] Some farmers also began to divorce themselves from the commission system by selling strawberries to dealers at the shipping point, though this does not appear to have been adopted extensively.[59,60]

The introduction of refrigerator cars in the mid to late 1800s substituted speed for better fruit preservation, reducing grower risk and improving sale prices by mitigating the impact of delays on fruit condition. Attempts to refrigerate with ice in the 1840s had ended in failure, causing most growers to discard the idea completely. One exception was Parker Earle, an Illinois strawberry grower, who continued to run trial fruit shipments on re-purposed dairy cars. He equipped them with containers capable of holding several tons of ice, essentially turning them into mobile iceboxes, later designing cars with even larger ice compartments for longer trips. Earle was also the first to discover the value of precooling; by storing fruit in cooling houses for 24 hours prior to shipping, he delayed the onset of spoilage, ensured even temperatures throughout the cargo, and reduced the melting rate of ice while

[53] Morris, "Tilton's Journal of Horticulture, Vol 6", pp. 287–288.

[54] Farmer, *New Strawberry Culture*, pp. 29–30.

[55] Fletcher, *The Strawberry in North America*, p. 55.

[56] Williams, "The Horticulturist, Vol. 24", p. 281.

[57] Farmer, *Farmer on the Strawberry*, p. 25.

[58] Parry, "The Horticulturist, Vol. 26", p. 99.

[59] Morris, "Tilton's Journal of Horticulture, Vol 6", p. 289.

[60] Earle, *Development of the Trucking Interests*, p. 448.

in transit. While initially slow to adopt, it has since become indispensable to the modern agricultural supply chain.[61] Refrigerator cars also took on a secondary role as storage units for unsold fruit, reducing pressure on commission merchants to sell their entire stock before markets closed.[62] These cars had their own barriers to overcome before they were more widely adopted: poor air circulation led to uneven cooling (along with damage from freezing), and the excess moisture from melting ice accelerated fruit decay. Human error was an additional risk; rail agents would sometimes fail to re-ice the cars between destinations.[63]

While the effects of cultural changes were less notable, they also played a role in improving the strawberry supply chain. Branding - and associated reputation - had emerged as a method to mitigate risk both from suppliers and the market. Some nurseries began supplying their salespeople with trademarks to identify them, although not to great effect. In place of legal authorities, horticultural publications exposed fraudulent nurseries and sellers,[64] and were expected to inform their readers whether a variety was valuable or "a humbug."[65] To improve their own sales, growers were advised to establish a reputation with local buyers - stenciling labels on their crates and ensuring their produce was uniformly high quality.[66] Growers were also advised to adopt only a few varieties at a time, limiting themselves to ones that were attractive, well adapted to the region, and produced at different times of the year - the Wilson, one of the earliest strawberry varieties available, was almost always a safe choice.[67] Variety specialization was also another way for growers to establish their reputation in the market and increase prices.[68] In response to poor market seasons, growers focused on improving the appearance of their fruit, using mulch to prevent dirt accumulation. Mulching had the additional benefit of enhancing soil moisture retention.[69] Farmers also began to adopt non-returnable "gift" crates - although less sturdy, they were significantly lighter and a quarter as expensive than the standard wooden ones. According to Lawrence Farmer, a grower and horticultural author from New York, these gift crates were extensively adopted in regions like the Mississippi Valley; this is likely due to the region's higher costs of freight.[70]

3.3 Costs and Profits in Commercial Production

In an article published in the *Magazine of Horticulture*, Charles Hovey criticized market growers for being slow to adopt new methods or varieties, especially those associated with intensive culture. However, after they were proven commercially successful, they rapidly diffused through farming communities.[71] Evidence supports the economic rationality of this behavior. The additional cost of intensive cultivation could be exorbitant - one grower estimated the additional labor and inputs of intensive cultivation would cost another $150

[61] Earle, *Development of the Trucking Interests*, pp. 446–447.
[62] Hale, "Cyclopedia of American Horticulture, Vol. 4", pp. 1733–1734.
[63] Commings, "The Horticulturist, Vol. 24", p. 98.
[64] Hayter, "Horticultural Humbuggery", pp. 210–212.
[65] A. Downing, "The Horticulturist, Vol. 5", p. 48.
[66] Putney and Woodward, *How to Grow Strawberries*, p. 12.
[67] Parry, "The Horticulturist, Vol. 26", p. 98.
[68] Williams, "The Horticulturist, Vol. 26", p. 261.
[69] Ibid., p. 263.
[70] Farmer, *Farmer on the Strawberry*, pp. 26–27.
[71] Hovey, "Magazine of Horticulture, Vol. 27", pp. 339–343.

per acre, roughly triple his original outlay and approaching the annual net profit of an operation.[72] Availability of inputs was an additional limiting factor:

> "Where are we all to get our sixteen inches of manure to fill a three foot trench, or even eight inches, or a foot of it for a two foot trench? No, no. That may do for a rich man with only a few rods of ground, near a large town, or a city. But it won't pay in a crop."[73]

Hovey himself claimed that Boston growers would have more widely adopted his namesake seedling except for the difficulty of acquiring sufficient fertilizer.[74] The benefit of greater intensity was also affected by the relative price of inputs to the cost of acquiring more land. One grower in Hammonton, New Jersey, claimed that thousands of acres of land in the region were available "at such rates as to make it desirable for all, whether rich or poor, to locate here"[75] - to put this in context, "adequate" soil could be found elsewhere for roughly $100 an acre.[76] As one farmer reported spending $70 on an acre's worth of manure, it was likely more economical in some regions to cultivate greater acreage than to procure large quantities of fertilizer.[77] The Wilson was a stable outside option: although it was the cheapest strawberry sold in the market, it could be grown for half the cost of alternatives.[78]

While there is insufficient data to verify Hovey's claims about the decisions of market growers, their behavior mirrors the predictions of economic theories of innovation adoption. Griliches' (1957) work addressed the development of hybrid corn - locally-specific varieties with higher production - and the diffusion of these technologies throughout corn-producing states. He found that adoption patterns were well-represented by a logistic growth curve, $P = \frac{K}{1+e^{-(a+bt)}}$, with the "rate of acceptance" (b) affected by the magnitude of increased profits in a region, but also correlated with a constructed measure of the region's similarity to the Corn Belt.[79] As discussed by Mansfield in 1961, the general S-shape of this diffusion curve is partially a result of imitation among technology adopters and the process of learning by doing; early adopters accumulate information and experience, while other producers observe them and subsequently reduce their own adoption risk. Both observations and personally attained experience will also reduce the cost of employing the technology, whether through improvements in efficiency or by reducing the educational burden. By demonstrating the profitability of the technology, other producers are encouraged (or through competition, pressured) to adopt themselves. Higher estimates of profitability encourage faster rates of adoption, but even when the impact remains ambiguous producers may still be influenced by the decisions of their competitors.[80]

Just and Zilberman (1983) would later examine the impact of farm size and risk perception on technology adoption. In their model, a farmer may choose to invest in a new

[72] Richard, "The Horticulturist, Vol. 14", p. 369.
[73] Anonymous, "The Horticulturist, Vol. 4", p. 144.
[74] Hovey, "Magazine of Horticulture, Vol. 27", pp. 339–343.
[75] N., "The Horticulturist, Vol. 20", p. 149.
[76] Williams, "The Horticulturist, Vol. 24", pp. 321–322.
[77] Williams, "The Horticulturist, Vol. 27", p. 132.
[78] Reuben (*pseudonym*), "The Horticulturist, Vol. 21", p. 309.
[79] Griliches, "Hybrid Corn".
[80] Mansfield, "Technical Change and the Rate of Imitation".

technology that allows them to grow a higher-value, potentially riskier crop that requires some form of "modern" input. One result was that farm size is inversely correlated to the amount of land dedicated to this new crop if:

1. Relative risk aversion is increasing, and;
2. Variability of modern technology is sufficiently large relative to traditional technology.[81]

Although the economic role of risk aversion is subject to debate, there are clear parallels between the findings of these papers and strawberry production. Hovey's assessment of market growers strongly implies that, along with profit potential, imitation was a major impetus behind their adoption of new technology. This also suggests at least one explanation for disparity in regional production. Similar to Griliches' analysis of hybrid corn adoption, the effect of imitation on technology adoption decisions was much weaker between strawberry growers in dissimilar regions; as discussed in Chapter 2, growers were acutely aware that experiential knowledge of strawberry cultivation was by no means universally applicable. Evidence also indicates that greater cultivation intensity was associated with higher though far more variable profits. It is feasible that market growers - at least those that were already engaged in extensive cultivation - would only partially adopt more intense production methods as a way to mitigate risk.

3.3.1 Discussion of Profits and Sample Crop Budget

Market conditions following the end of the Civil War had convinced growers that strawberries had ceased to be remunerative without significant capital expenditure. Investment, however, was not sufficient to guarantee economic success. For example, during his tenure as editor of *The Horticulturist*, Henry Williams claimed that it cost him $500 per acre to establish a bed, $150 of which was spent on boxes alone.[82] Despite this sizeable outlay, his per-acre profits were just $100 that year, or the average for market growers in the Mid-Atlantic region.[83] In contrast, John Knox of Pittsburgh realized average annual net returns of $1,400 per acre, with an estimated annual production cost of only $200.[84] Strawberry variety and the intended market were thought to be the primary determinants of this profit gap. Knox specifically cultivated Jucunda strawberries - higher quality than the Wilson - and sold them in individual gift baskets for up to $1 per quart; some portion was also sold directly to consumers, bypassing the 10 percent fee of the commission merchant.[85] Based on references from historical literature, a rough sample crop budget is provided to illustrate a grower's expected returns.

Yields and Profits: As a general rule, larger farms tended to be less productive than smaller, more intensely cultivated ones, and their production decisions - less soil cultivation, use of matted rows - tended to limit them to hardier but lower-value varieties like the

[81] R. Just and Zilberman, "Farm Size and Technology Adoption".
[82] Williams, "The Horticulturist, Vol. 26", p. 263.
[83] Morris, "Tilton's Journal of Horticulture, Vol 6", p. 30.
[84] Fletcher, *The Strawberry in North America*, pp. 46–47.
[85] Williams, "The Horticulturist, Vol. 26", p. 61.

Wilson. Plantations in Maryland, Delaware, and New Jersey averaged yields of 1,500 quarts to the acre - slightly more than a ton - for an average of $100 in profit;[86] 3,000 quarts an acre was considered unusually high, even unachievable for most.[87] In contrast, it was reportedly possible to produce from 4,000 to 6,000 quarts an acre under intensive cultivation, typically for much higher returns.[88,89] Profits were reliably higher than for other crops, but the supply response to high prices was rapid and generated instability. Returns of $200 per acre were considered to be satisfactory for most growers, although it could reportedly vary from anywhere between $100 to $800.[90,91] On very rare occasions, a farmer's profits might be well in excess of $2,000, although this became more unusual after the extension of rail and the close of the Civil War increased supply.[92] In other circumstances - years where markets were heavily over-supplied - a farmer might instead stand to lose more money from hiring pickers than just abandoning the field. A horticultural correspondent in Rochester claimed an income of around $260 on five-eighths of an acre,[93] and growers near Boston, a region known for the general popularity of high culture, were reported to earn $800 in profit on a regular basis.[94]

Land: Given the geographic range of strawberry production, land prices could differ appreciably from one district to another. It was generally accepted that strawberry production tolerated a wide swathe of land characteristics, including soil type, topology, and availability of water - a common adage was that any soil that could grow a crop of corn or potatoes could grow strawberries. Inputs or cultural adjustments were used to compensate for deficiencies in land, and many new entrants into strawberry production cultivated land they already possessed.[95] This appears consistent with the limited available data; at different points in time, farmers faced prices of:

- $60 per acre to purchase farmland (5 miles north of Albany, NY. 1849.)[96]
- $10 of interest on an acre (Cinnaminson, NJ - 3 miles east of Philadelphia. 1871.)[97]
- $21 annual rent on an acre valued at $300 (20 miles east of Syracuse, NY. 1872.)[98]
- $10 annual rent (40 miles north of Syracuse, NY. 1891.)[99]

The editors of *The Horticulturist* mention fertile soil as being easily procured at $100 an acre. Growers could find land that cost less at the outset, but would likely have to compensate for

[86] Morris, "Tilton's Journal of Horticulture, Vol 6", p. 30.
[87] Williams, "The Horticulturist, Vol. 24", p. 230.
[88] Williams, "The Horticulturist, Vol. 26", p. 220.
[89] Rolliffe, "The Horticulturist, Vol. 24", p. 237.
[90] R. Pardee, *A Complete Manual*, pp. 40–41.
[91] Morris, "Tilton's Journal of Horticulture, Vol 6", p. 30.
[92] Fletcher, *The Strawberry in North America*, pp. 42–49.
[93] Watts and Southworth, "The Horticulturist, Vol. 7", p. 433.
[94] Hovey, "Magazine of Horticulture, Vol. 28", p. 363.
[95] R. Pardee, *A Complete Manual*, pp. 9–14.
[96] "Cultivator" (*pseudonym*), "The Horticulturist, Vol. 4", p. 53.
[97] Parry, "The Horticulturist, Vol. 26", p. 101.
[98] Williams, "The Horticulturist, Vol. 27", pp. 131–132.
[99] Farmer, *Farmer on the Strawberry*, p. 26.

deficiencies through increased fertilizer and tillage.[100] The impact of railroads on the average land expenditure of strawberry farmers is ambiguous; while rail increased the value of nearby acreage, it also allowed strawberry growers to move further away from urban centers.[101]

Capital and Input: Equipment for small operations might consist of hand implements and tiles for improving subsoil drainage. Simple tools were inexpensive, and could be acquired for $1 to $2 from a nursery or blacksmith. Larger operations usually invested in a horse-drawn plough and cultivator to reduce labor input; advertisements imply these cost between $5 to $15.[102] Fertilization for both new beds and renewed ones had become virtually mandatory, although the "best" kind had yet to be determined; common soil amendments included stable manure, vegetable compost, bone meal, or mixtures of lime and ashes.[103] The amount depended on the grower and on their soil quality, and ranged from a few hundred to a few thousand pounds per acre.[104] Price was also influenced by material and nutrient content. Farmer applied commercial fertilizer that contained 10 pounds each of ammonia, potash, and phosphoric acid per 100 pounds,[105] worth $3.60 in total; the remainder was comprised of filler to facilitate use.[106] Another grower purchased 800 pounds of bone ash and calcium carbonate per acre for $25, while a third acquired 35 "loads" of manure for $70; Farmer's article tentatively suggests this measure corresponded to roughly 50 pounds.[107,108] Long-distance shipping required the use of strawberry chests and boxes, which cost $3 to $4 per hundred. Growers were obliged to maintain an excess supply, and the outlay could become exorbitantly expensive; one grower had invested $1,000 in boxes for his operation,[109] and another reported that he spent $100 per acre on boxes alone, comprising 45 percent of his pre-shipping costs.[110] Mulching had become more common towards the end of the 1800s, and cost growers an additional $15 to $25 in material and labor.[111]

Price: Prices varied with available supply/timing of harvest, quality, and cultivar. Common berries - typically Wilson - sold for 20 to 25 cents per quart at the beginning of the season, and declined to 10 or 15 cents towards the end. Higher quality cultivars were often priced between 25 to 50 cents a quart, and could reach $1 to $1.50 under the right circumstances.[112] Variation was significant and could occur rapidly, as seen in excerpts from *The Horticulturist*, pictured in Figures 3.3 and 3.4 on the following page. It is hard to overemphasize the effect of local supply, or lack thereof, on prices: in 1871, the Rural Club of New York noted that berries sold for 30 cents a quart in New York "were reshipped to Boston, and sold there for fifty to ninety-five cents."[113] Early shipments to markets, whether by climate or cultivar selection,

[100] Williams, "The Horticulturist, Vol. 24", pp. 321–322.
[101] Coffman and Gregson, "Railroad Development and Land Value", pp. 191–193.
[102] Bridgeman, *Annual Catalogue*, pp. 29–31.
[103] Merrick JR., *The Strawberry and Its Culture*, pp. 12–14.
[104] Williams, "The Horticulturist, Vol. 24", p. 131.
[105] These are the standard fertilizer macronutrients - nitrogen, phosphorus, and potassium - used today.
[106] Farmer, *Farmer on the Strawberry*, p. 45.
[107] Parry, "The Horticulturist, Vol. 26", p. 101.
[108] Williams, "The Horticulturist, Vol. 27", p. 132.
[109] Morris, "The Illustrated Annual Register of Rural Affairs, Vol. 1", pp. 289–291.
[110] Rolliffe, "The Horticulturist, Vol. 24", p. 237.
[111] Farmer, *Farmer on the Strawberry*, p. 26.
[112] R. Pardee, *A Complete Manual*, pp. 14, 40.
[113] Williams, "The Horticulturist, Vol. 26", p. 264.

could be immensely profitable. This phenomenon has since received more formal treatment in economic literature; Parker and Zilberman (1993), for instance, document empirical evidence of how retail prices may experience immense fluctuations between demand season and off-season, and that farmers able to capture the market either before or after the primary season tend to generate corresponding profits.[114]

Figure 3.3: Seasonal prices in New York.

	Matilda per qt.	Wilson per qt.
June 8	45 cents	24 cents.
10	36 "	22 "
14	21 "	16 "
15	15 "	10 "
17	27 "	20 "
20	27 "	18 "
21	24 "	18 "
22	24 "	16 "
23	24 "	15 "
24	24 "	18 "
27	30 "	18 "

Source: *The Horticulturist*, 1871.

Figure 3.4: Prices in Cincinnati.

To show the relative value of strawberries in market, I may mention that the following varieties ranged, on the same day, in Cincinnati, at

Fifty cents for Jucunda.
Forty cents for Triomphe de Gand and Seth Boyden.
Thirty to thirty-five cents for Kentucky and Agriculturist.
Twenty cents for Chas. Downing.
Ten to fifteen cents for Wilson's Albany.

Source: *The Horticulturist*, 1873.

<u>Plants:</u> The cost of acquiring strawberry transplants depended on the cultivar's marketable qualities, including size, appearance, and productivity. Novelty also played an important role, as speculation inflated prices tremendously; a thousand plants might cost anywhere between \$3 to \$30, and the same quantity of newly-introduced cultivars could exceed \$100.[115] A farmer's between-row and within-row spacing determined the number of plants required, and was influenced in part by the mode of cultivation - the use of horse-drawn equipment, for example, necessitated greater space between strawberry rows.[116] Supplying an entire acre could require several thousand transplants, but a farmer could sacrifice some fruit production in order to propagate their own runners. According to an Ohio nurseryman, several hundred plants could be propagated from a dozen, attenuating production cost and

[114] Parker and Zilberman, "Hedonic Estimation of Quality Factors".
[115] Crawford, *Crawford's Strawberry Culture with Catalogue*, pp. 20–21.
[116] R. Pardee, *A Complete Manual*, pp. 36–38.

providing a secondary source of income should the farmer choose to sell the additional runners. Allotting greater space between plants within the row increase the size of individual berries but reduced their number, while allowing the plants to run together was cheaper and more productive at the expense of quality.[117]

Labor: Labor requirements in strawberry cultivation was heavily concentrated in harvesting, although bed establishment could also be highly demanding - and costly - when performed by hand. One Albany gardener estimated it took 12 man-hours to establish a twentieth of an acre, not including time spent plowing and setting plants.[118] Extensive production required less labor to establish, as it made more use of horse-drawn equipment and allowed runners to grow instead of trimming them. However, it also demanded more labor during harvesting - smaller berries in matted rows took longer to find and were harder to pick. Richard Pardee's 1865 cultivation manual claimed $15 to $25 as an average expenditure on ground preparation and maintenance for extensive culture;[119] in 1891, Farmer placed his costs at a slightly higher $45, but additionally included $10 in labor for setting plants and mulching.[120] In comparison, an intensive grower in Oneida established a strawberry bed for closer to $130, out of a total of $350 for pre-harvest expenditures.[121] As a rule, harvesting was the largest individual expense for both intensive or extensive operations, and could be equivalent to all other labor expenditures combined. Most growers reported wage rates of 2 to 2.5 cents per quart: $40 to $50 for an average market grower, or double to triple for an intensive one. With an additional 4 to 5 cents for freight, commission, and hauling, it cost a farmer around 7 or 8 cents to send each quart to market; according to one grower, this accounted for a third of his entire expenditures in a year.[122] When household labor became insufficient for picking strawberries, farmers employed local women and children. Later, with the expansion of commercial production, professional pickers were also hired; these laborers were migratory, and made a living by moving from southern states to northern ones over the course of the season.[123] It was common for farmers to provide pickers lodging and possibly meals to ensure they continued to work for the duration of the season. Outside labor often entailed hiring a superintendent and might cost a grower an additional $15 per acre.[124]

Table 3.1 approximates a farmer's potential crop budget. These figures come with the caveat that data limitations are significant; mulch and manure, for example, varied widely in price and content, and their measurements were not standardized. This is also under the assumption of convenience that our farmer disposes of the entire crop at the same price. Final profits are likely biased downward: capital expenditure diminished after the first year, and farmer/household labor attenuated costs, especially if they cultivated their own planting stock. It is also highly likely that extensive farmers benefited from input or capital efficiencies that are otherwise not observable.

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[117] Crawford, *Crawford's Strawberry Culture with Catalogue*, pp. 5–11.
[118] "An Albany Subscriber" (*pseudonym*), "The Horticulturist, Vol. 4", p. 530.
[119] R. Pardee, *A Complete Manual*, pp. 40–41.
[120] Farmer, *Farmer on the Strawberry*, p. 26.
[121] Williams, "The Horticulturist, Vol. 27", p. 132.
[122] Rolliffe, "The Horticulturist, Vol. 24", p. 236.
[123] Crawford, *Crawford's Strawberry Culture with Catalogue*, p. 11.
[124] Farmer, *Farmer on the Strawberry*, pp. 18–19.

Table 3.1: Sample Crop Budget for Strawberry Production, 1 Acre

Item	Budget Range	Notes
Land rental	\$10 to \$20	Assumed rental rate around 5-10% of land value.
Plants	\$40 to \$60 (Wilson) \$50 to \$75 (Jucunda) \$90 to \$135 (Sharpless)	10,000 to 15,000 plants, less if self-propagated.
Input	Manure: \$25 (ext.) to \$80 (int.) Mulch: \$17 (ext.) to \$50 (int.)	Includes labor; documents aggregated these figures.
Labor (excl: harvest, mulch, manure)	Plowing: \$4 to \$6 Setting plants: \$5 to \$25 Cultivation (if horse): \$15 to \$30 Cultivation (if hand): \$80 to \$100	Does not account for initial cost and upkeep of the horse, but this is assumed to be a fixed cost.
Harvesting	Picking: 2 cents/quart Shipping: 4 cents/quart Supervision (for ext.): \$15	Outlay could be reduced by household labor, though this carried an opportunity cost.
Capital	Boxes: 2 to 5 cents/quart Tools (shed, hoe, plow): \$5 Horse cultivator: \$15	Box price based on quality.
Theoretical Production	Extensive: 2,000 quarts Intensive: 4,000 quarts	
Pre-Harvest Cost	Extensive: \$146 to \$218/acre Intensive: \$306 to \$421/acre	Intensive production assumes hand cultivation, non-Wilson strawberries, quality boxes, and no supervision
Total Cost	Extensive: \$306 to \$378 Intensive: \$746 to \$861	
Prices	"Low quality": 22 cents/quart "High quality": 40 cents/quart	Derived from New York prices (figure 2.3) and reduced 10% to account for commission.
Profit	Extensive: \$62 to \$134/acre Intensive: \$739 to \$854/acre	

Sources: *The Horticulturist* (1849, 1869, 1872), Pardee (1856), *The Illustrated Rural Register* (1869), Crawford (1881), Farmer (1891), *Annual Descriptive Catalogue of Seeds* (1896)

These figures suggest an intensively cultivated acre was substantially more expensive to establish than an extensive one, but that the additional outlay was more than accounted for by the additional profit. However, while we have assumed a constant disposal price for convenience, intensive cultivators were also subject to greater price volatility; if we were to substitute the minimum prices seen in Figure 3.3, an intensive grower would end the season deeper in debt than an extensive grower. It is also important to note how large of a proportion harvesting costs were of the overall budget, and how sensitive final profits were to labor wage rates.

3.3.2 Soil Health and Pest Pressure in the Late 1800s

Early strawberry cultivators, like many of their contemporary agricultural producers, did not engage in widespread or systematic crop rotation. However, developing issues with both pest pressure and soil exhaustion encouraged wider adoption by the end of the 19th century. Though earlier cultivation manuals had stated - perhaps hyperbolically - that strawberries were uniquely exempt from predation or disease, future texts were less cavalier. James Merrick discussed the threat posed by May beetle larvae at length in his 1870 text, *The Strawberry and Its Culture*. May beetles bred in grassland and pastures, and growers converting these areas directly to strawberry plots would unwittingly allow larvae to feed on the roots of strawberry crops. A May beetle infestation was asymptomatic until the root damage was severe enough to cause wilting, and any treatments that were fatal to the larvae were similarly fatal to the plant. Merrick recommended preventing infestation by cultivating hoed crops for one or two years prior to planting strawberries - regularly plowing the soil eliminated breeding grounds and exposed larvae to predators and the elements.[125] The importance of this type of rotation was reiterated in Matthew Crawford's *Strawberry Culture* in 1880, as well as Lawrence Farmer's *Farmer on the Strawberry* and *The New Strawberry Culture* in 1891 and 1911 respectively. Farmer noted that the larvae were particularly abundant in old strawberry beds, and recommended fruiting a plot of strawberries for only a single year to avoid infestation.[126]

Some regions had also started to experience issues with soil exhaustion, likely a direct result of the cultivation methods endemic to the Wilson strawberry. As previously mentioned, part of the Wilson's immense popularity was its reliable production under less-than-favorable conditions. Fletcher's description of broadcast training implies that rotation was largely ignored; when weeds became an issue or vines were too old, they were plowed under to let new runners take their place. These plantations were sometimes kept for 10 to 15 years, with cultivation limited to mowing and burning the leaves after harvest. Growers' attitudes began to shift after 1870, which Fletcher attributed to falling demand for low quality berries and a desire for greater drought resilience. A modified matted row culture reemerged as a compromise between risk reduction and yield maximization/cost minimization. Strawberry rows were narrowed and spaced widely enough apart to cultivate the soil between them, while the number of plants allowed to develop from runners was substantially reduced. In some

[125]Merrick JR., *The Strawberry and Its Culture*, pp. 34–35.

[126]Farmer, *Farmer on the Strawberry*, pp. 8–9, 16–17.

areas, the lifetime of a plantation fell from 10 or 15 years to just two.[127] Growers near Boston had even adopted an "annual" culture by 1870, plowing their strawberry beds under after a single year and rotating the land to another crop. Common rotations included potatoes or "green manure" crops like clover, which was simply plowed under instead of harvested. Merrick also stated that growers found it better to avoid raising strawberries in succession, implying that by this time growers had become cognizant of what would later be referred to as the "replant problem."[128] Soil exhaustion is absent from Crawford's work, but Farmer's own experience with consecutive plantings "[led him] to suppose that strawberry fruit takes out of the soil something not readily restored by manure."[129] Fletcher noted that continuous cultivation left land "berried out" or "strawberry sick" - by the early 1900s, growers would typically seek out virgin land for new beds or adopt multi-year rotation patterns.[130]

Despite the comparative simplicity of early capital, investment had already been influenced by rotation. Packing houses - sheds used to house strawberries before crating - were erected or converted from nearby buildings, and could be used to store berry crates after harvest. Rotating strawberries from one location on a larger farm to another often required the construction of a new packing house; the wage system required pickers to submit their own boxes, and a new shed reduced the time spent walking between the foreman and the row. Fletcher recommended constructing one shed in the center of every four to five acres.[131] This limited investment; packing houses were constructed to prevent sun exposure, but were insufficient for cooling or to provide shelter from rain. In 1891, Lawrence Farmer discussed plans for a sturdier packing house on rollers, allowing him change its location from year to year. However, this contrivance is absent from his 1911 publication, possibly indicating it was discarded.[132]

3.4 The Early 20$^{\text{th}}$ Century

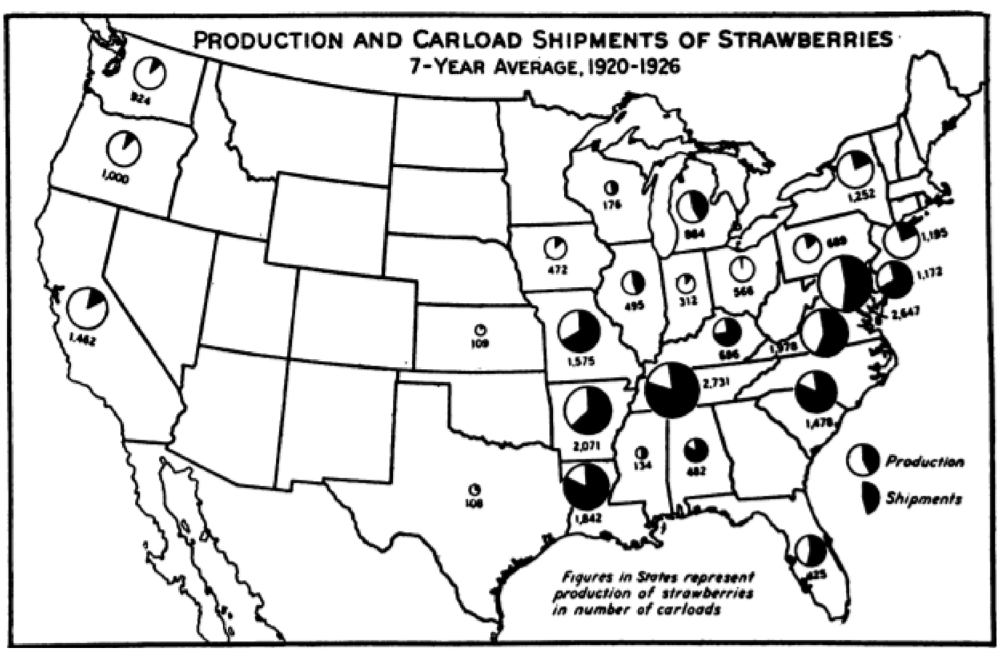
Significant progress had been made in strawberry culture in the 50 years following the introduction of the Wilson, turning the most popular small fruit "from a luxury into a necessity."[133] At the close of the century, the average strawberry farm was slightly larger than half an acre and produced over 900 quarts, a per-acre yield of almost two tons. Improved varieties, greater acreage, larger yields, and vigorous competition had significantly lowered prices for even the highest quality berries. Cheaper produce and faster transportation altered urban diets; cities demanded ever-greater quantities of both fresh and processed fruits and vegetables.[134] Strawberry production had extended well to the south, lengthening the market season from three weeks to three months, and lesser quantities were available both earlier and later in the year. Fletcher also attributed some of the increase in individual holdings to the end of the Civil War; former slaves sought out relatively high-wage employment in

[127] Fletcher, *The Strawberry in North America*, pp. 87–94.
[128] Merrick JR., *The Strawberry and Its Culture*, pp. 19–28.
[129] Farmer, *Farmer on the Strawberry*, p. 42.
[130] Fletcher, *Strawberry Growing*, p. 44.
[131] Ibid., pp. 166–173.
[132] Farmer, *Farmer on the Strawberry*, pp. 27–28.
[133] Shinn, "California Horticulturist, Vol. 9", p. 349.
[134] McCorkle, "Moving Perishables to Market", p. 43.

the strawberry industry, taking positions as hired laborers as well as operating their own farms.[135]

A longer supply chain meant that distance to the consumer and the timing of harvest became important determinants of production practices. In 1881, the editor of *American Gardening* described commercial production as occurring in "two sharply defined systems, each with its appropriate modes of cultivation... the *home market* and *shipping system*."[136] A farmer producing for the home market was akin to a local retailer, usually operating within 40 miles of their consumers and directly responsible for marketing their own produce, while a farmer participating in the shipping system tended to cultivate acreage in a large strawberry district and market their produce through commission merchants at distances of hundreds of miles. Local production was generally preferred to long-distance shipping; prices were higher and profits more consistent, as fewer suppliers meant the market was less prone to cycles of overproduction. It also lacked many of the risks associated with the shipping system, including train delays, lapses in refrigeration, and misconduct on the part of commission merchants. However, conducive locations for home markets - areas not yet adequately supplied - were not always readily available.[137]

Figure 3.5: Proportion of carload shipments, 1920-1926.



Source: Strowbridge, *Origin*, 1930.
Unshaded segments are production "unaccounted for:" local consumption, motor-truck shipments, processing, and spoilage.

The size of the circles seen in Figure 3.5 represent the approximate number of carloads produced in a given state, while their shaded portions represent the proportion of each

[135]Fletcher, *The Strawberry in North America*, pp. 68–69.
[136]Hexamer, "The American Garden, Vol. 2, No. 1", p. 10.
[137]Fletcher, *Strawberry Growing*, pp. 3–5.

state's production that was shipped to outside markets. From the figure, it is clear that southern strawberry industries were highly dependent on external consumption; however, their intended markets were often several states away. This dilemma was central to how the strawberry supply chain would develop in the region.

3.4.1 Strawberries in the South

Early commercial production in the south had been limited to coastal cities connected by short, water-based trade routes. Norfolk strawberries could be marketed as far north as New York City by the 1850s, though this approached the limit of an unrefrigerated supply chain; the trip alone took 36 hours and produce often arrived in questionable condition. Better transportation in the 1860s relaxed these constraints, and within a decade growers as far south as Charleston were shipping tens of thousands of quarts daily to New York. For inland states, commercial cultivation followed the extension of railroads; Mississippi, Alabama, Tennessee, and Louisiana began marketing strawberries around 1870, followed by Arkansas in 1873, Florida in 1878, and Missouri in 1887.[138,139] From 1900 onward, production in the Central South expanded prodigiously, and by the 1920s, four states - Arkansas, Louisiana, Missouri, and Tennessee - accounted for 40 percent of the roughly 200,000 acres cultivated nationwide. With the exception of Louisiana, these states principally supplied the growing urban populations in the Midwest, including Detroit, Minneapolis, and Cincinnati; Chicago, now the second-largest city in the US, consumed almost a quarter of the region's total production.[140,141]

Strawberry production in the South possessed several inherent advantages over the North, including more suitable climates, cheaper labor, earlier fruit maturation. However, they also lacked an equivalent consumer base.[142] Developing a southern industry was thus contingent on access to northern markets, and heavily dependent on a robust shipping system and related capital. Rail companies played an active role in developing local industries in order to generate additional traffic for their own lines; besides furnishing infrastructure for the shipping system, they also solicited farmers to enter production, offering them financial support, the use of specialized railcars, and assurances of fast train schedules.[143] Refrigeration for strawberries - and southern agricultural exports in general - also required investment in local ice-manufacturing capacity. Unlike northern states, the south lacked naturally occurring ice, which forced rail companies to import it and drove up the costs of transportation. Local entrepreneurs assessed a variety of ice-manufacturing equipment during the 1870s, typically in cities where a business would be shielded from competition with the natural product. Ice production soon became a thriving industry in its own right; by 1890, southern states had 165 plants in operation, and by 1900 manufacturers supplanted natural ice shipments as far north as Pennsylvania.[144]

[138] Fletcher, *The Strawberry in North America*, pp. 68–74.

[139] F. L. Thomsen and G. B. Thorne, *Economics of Strawberry Production and Marketing In Missouri*, p. 6.

[140] Strowbridge, *Origin and Distribution*, pp. 58–67.

[141] Brannen and Dickey, *Strawberry Production and Marketing in Arkansas*, p. 22.

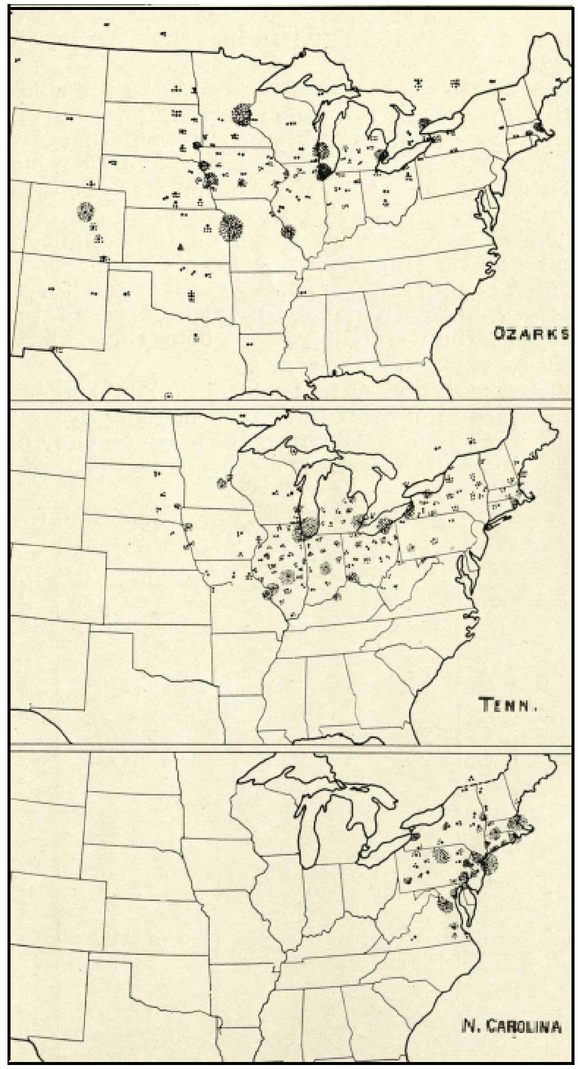
[142] McDowell, "The Economic Impact of Technology on Strawberries", pp. 1786–1787.

[143] McCorkle, "Moving Perishables to Market", pp. 48–59.

[144] Anderson Jr., *Refrigeration in America*, pp. 86–88.

Although refrigeration and related infrastructure had made southern trade in perishable goods feasible, it was still expensive both financially and in terms of product degradation. Districts came to occupy seasonal niches predicated on avoiding direct competition with northern growers and their immense competitive advantage.[145] Shipping rates from the Central South to New York or Boston, for example, were anywhere from 20 to 100 percent higher than those from Virginia or North Carolina, and longer travel times further restricted redistribution to smaller markets nearby.[146] Rail companies were also frequently accused of opportunism by farmers of perishable goods, who believed them to be inflating freight charges; numerous complaints were lodged with the Interstate Commerce Commission in the hopes of procuring outside intervention.[147,148]

Figure 3.6: Shipment Distribution, 1924.



Source: Brannen and Dickey, *Strawberry Production*, 1927. Each dot represents a carload shipment from the respective region to the indicated market.

Southern producers' early shipments commanded impressive premiums that more than compensated for additional transportation costs. However, what was considered "early" was steadily pushed back as the supply chain extended further south.[149] In the 1850s, Norfolk strawberries sold for anywhere from 50 cents to $1.50 per quart; by the 1890s, wholesale prices had declined to just 6 to 14 cents.[150] Average prices for Charleston growers fell from an average of 57 cents per quart in 1872 to 12 cents by 1881.[151] For the earliest producers, uncontested markets generated potentially astronomical prices; shipments from Florida to New York began as early as December, when even "little, hard, acid berr[ies]"[152] could fetch between $2 to $2.50 per quart.[153] However, novelty was short-lived; according to one Florida grower, an average of 16 or 17 cents was considered

[145] Strowbridge, *Origin and Distribution*, pp. 48–67.

[146] Wicks, *Strawberry Growing in Arkansas*, pp. 6–15.

[147] McCorkle, "Moving Perishables to Market", pp. 60–61.

[148] Clements, "Truck Farmers' Association V. Northeastern R.R. Co.", pp. 295–300.

[149] Agricultural literature now groups districts into categories of production - Winter, Early Spring, Midspring, and Late Spring.

[150] W. Taylor, "The American Garden, Vol. 12, No. 11", p. 658.

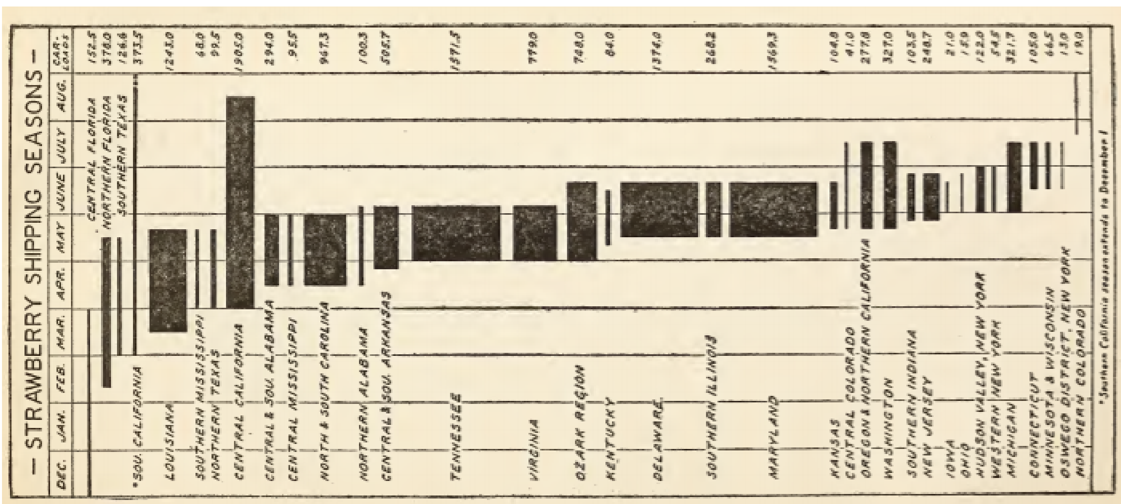
[151] Hexamer, "The American Garden, Vol. 2, No. 1", p. 10.

[152] Powers, "The American Garden, Vol. 11, No. 6", p. 327.

[153] Hexamer, "The American Garden, Vol. 6, No. 6", p. 145.

a successful season.[154] Moreover, if a district closer to a market began production, further shipments became economically unviable. Growers in these situations often abandoned harvesting partway through the season, and in some states, up to a quarter of total production might be left unpicked.[155] Florida, for example, ceased making shipments four to six weeks prior to the end of their actual bearing season; in the early spring, when weather became warmer, switching from ventilator to refrigerator cars doubled the price of shipping to northern markets. In Virginia, Norfolk growers had ten to fifteen days before production from Maryland and Delaware would conclude the season, as produce from these states would arrive in New York or Boston in better condition and at lower prices. This often cost Norfolk growers half their harvest.[156] Existing niches were also eroded by new entrants; Charleston, once an important strawberry district, dwindled in relevance after production began in North Carolina.[157]

Figure 3.7: Seasons by region.



Sherman et al., *Strawberry Supply*, 1914.

Figure 3.7 is a visual representation of each state's peak strawberry season and volume; bar length corresponds to the typical season duration, while bar area represents the total amount of strawberries produced in units of carloads. The figure reinforces how significant the amount of seasonal overlap was between producing regions, as well as the limited windows in which one region's growers might have to exercise market power. The exceptions to this are California and Florida, which have distinctly longer seasons that extend well outside the production periods of their competitors.

[154] Powers, "The American Garden, Vol. 11, No. 6", p. 327.
[155] Fletcher, *Strawberry Growing*, p. 207.
[156] W. Taylor, "The American Garden, Vol. 12, No. 11", pp. 657–658.
[157] Fletcher, *The Strawberry in North America*, p. 72.

3.4.2 Associations

In the eastern half of the United States, strawberry growers' associations were primarily formed in the south. Reliance on northern markets and long distance shipping necessitated greater cooperative efforts than in the North, which had a higher proportion of home market production.[158] The most fundamental functions of an association were to reduce transportation costs through cargo pooling and to improve market outcomes by coordinating members' shipments. Cooperation in shipping was essentially mandatory to reducing transportation costs. A farmer on four to five acres would take an entire season to produce a single railcar (10,000 to 15,000 lbs) worth of strawberries. Aggregating production and eliminating partial carloads lightened the financial burden on the individual farmer and allowed for regular market shipments.[159] Collective action also facilitated negotiation with rail companies over reductions in freight costs, and central coordination ensured that shipments were more evenly distributed.[160] Some associations would also fund market research, promoting consumption through advertising campaigns.[161] Aside from transportation and marketing, an association might also provide farmers with a line of credit during the season, or provision materials - fertilizer, tools, crates - as they entered into production.[162] Multiple reports confirmed these measures to be decidedly effective in improving economic outcomes; the Ozark Fruit Growers' Association in particular was credited with "bringing the price of strawberries...from about $1.00 net previous to its organization in 1905, to more than $2.20 in 1910."[163]

Despite these benefits, agricultural cooperation faced a variety of obstacles, and farmers were not always successful in establishing associations or in perpetuating them. Many were short-lived; of the 3,000 recorded by 1932, fully 50 percent had been shut down, and over a third had dissolved within five years of their inception. In some districts, the number of associations was excessive, resulting in an overall loss of efficiency through duplication of effort. Inter-association competition exacerbated the cobweb phenomenon of cyclical overproduction, as did the use of shipping volume as a metric of success for association leadership. These issues were pronounced in areas where truck crops were not a primary source of income, as associations had less incentive to judiciously manage members' production.[164,165] Fruit and vegetable associations in particular often struggled to maintain cohesion:[166]

> "...within recent years the tendency seems to have been away from rather than toward coordinated effort. It is to be hoped that the low prices of 1928 will induce the [strawberry] growers... toward the presenting of a united front."[167]

Farmers often chafed at the imposition of restrictions on acreage, and when prices were high

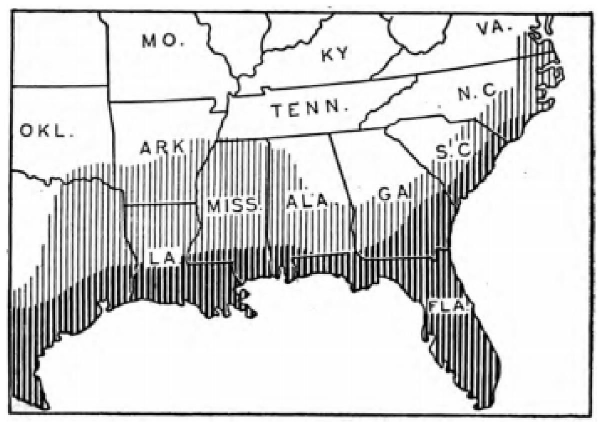
[158] Fletcher, *Strawberry Growing*, p. 201.
[159] Strowbridge, *Origin and Distribution*, p. 14.
[160] Stinson, *Strawberries*, p. 140.
[161] F. L. Thomsen and G. B. Thorne, *Economics of Strawberry Production and Marketing In Missouri*, pp. 83–94.
[162] R. Thompson, *The Agricultural Credit Situation in Louisiana*, pp. 14–15, 22.
[163] Chandler, *Co-operation Among Fruit Growers*, p. 9.
[164] F. L. Thomsen and G. B. Thorne, *Economics of Strawberry Production and Marketing In Missouri*, pp. 40–47, 103.
[165] McCorkle, "Southern Truck Growers' Associations", pp. 82–85.
[166] Ibid., pp. 95–98.
[167] F. L. Thomsen and G. B. Thorne, *Economics of Strawberry Production and Marketing In Missouri*, p. 114.

were more likely to deviate from collective action. Depending on the association's selling practices and the relative quality of their produce, they might also believe it to be more profitable to market as an individual. These setbacks aside, however, cooperation remained an integral part of mitigating risk within the shipping system, and southern farmers would continue to organize even in districts where they had previously failed.[168]

3.4.3 Southern Strawberry Economics

Although Southern production was heavily oriented towards the shipping system, there were still substantial variations in the cultural methods they adopted. Producers along the Gulf and South Atlantic coasts had early strawberry seasons as well as higher costs of production and transportation. In Florida, growers were faced with severe infestations of nematodes, which they dealt with by importing plants from northern states where nematodes were less prevalent. This initial stock was allowed to propagate for several months, at which point there were a sufficient number of runners to set for fruit production. Southern growers in other states also suffered losses from nematodes; however, they tended to set their field with imported northern stock directly, or otherwise simply acquired runners from local (ideally pest-free) nurseries. The adoption of hill culture was highest in the deepest parts of the south, and transitioned into "hedge-row" culture as cultivation moved further north. Hedge-row culture was an intermediate method between hills and matted rows, characterized by allowing a limited number of runners to take root to increase plant density (and nutrient competition) of an acre but not to the same degree as a matted row.[169] In many of these districts, the returns from early production justified intensive practices; plantations were typically kept for a single year before being plowed under re-set, and applications of commercial fertilizer ranged from 1,000 up to 2,500 pounds an acre.[170] Texas, Louisiana, and Florida growers were also unique among their southern peers in that they also adopted irrigation. In Texas and Louisiana, surface irrigation was most common; in Florida, growers utilized a mix of surface and more expensive sprinkler irrigation systems.[171,172]

Figure 3.8: **Cultural Methods, 1919.**



*The shaded area represents the "South Atlantic" region; the darker shading indicates the extent of hill culture.
Source: Darrow, *Strawberry Culture : South Atlantic and Gulf Coast Regions*, 1919.

Further inland, production became considerably less intensive, particularly in the large shipping districts of Arkansas, Missouri, and Tennessee. With lower transportation costs

168McCorkle, "Southern Truck Growers' Associations", pp. 94–98.

169Darrow, *Strawberry Culture: South Atlantic and Gulf Coast Regions*, pp. 8–14, 29–30.

170H. Thompson, "Cyclopedia of American Horticulture, Vol. 6", p. 3265.

171Brooks, Watson, and Mowry, *Strawberries in Florida: Culture, Diseases, and Insects*, pp. 492–493.

172Schilletter, Elwood, and Knowlton, *Changes in Technology and Labor Requirements*, pp. 6–7.

along with later seasons, the trade off between yield and quality was less advantageous, and most growers chose to cultivate in dense matted rows. Growers in Arkansas and Missouri reportedly eschewed even basic cultivation practices, including mulching, weeding, and even fertilization. Whatever positive yield effect the use of matted rows provided these growers, overall productivity in the region was low, and the high regional output instead reflected the immense amount of acreage under cultivation. Agricultural bulletins attributed these production decisions to low prices and the ready availability of land; the yield effect of additional input was insufficient to justify expenditures, and maintaining long-term soil quality was less profitable than planting to new acreage.[173,174,175,176] Using these bulletins, sample costs and profits are presented in Table 3.2 and Figure 3.9.

Table 3.2: **Central South Production Costs, late 1910s to mid-1920s.**

State	Avg. Yield (quarts)(1)	Cost (acre)	Avg. Price (quarts) (1)	Avg. Profit (acre)	Unit Cost (quarts)
Louisiana	1,434	$250 (2)	27 cents	$135	17.5 cents
Arkansas	1,274	$90-$100	16 cents	$105-$115	7-8 cents
Tennessee (3)	1,602	No data	12 cents	No data	No data
Missouri	1,634	$100-$110	12 cents	$90-$100	6.5 cents

(1) Averaged over 1921-1925. (2) Cost data extrapolated from Station bulletin.
(3) Crop budgets from 1914 (Fletcher, 1917a) suggest Tennessee costs were equivalent/slightly lower than Arkansas.
Sources: *Missouri Station Bulletin 262*, *Arkansas Station Bulletin 218*, *Marketing Louisiana Strawberries: 1921-1939*.

Figure 3.9: **Costs of Production, Florida and Southern US.**

Plant City, Florida; 1917

Interest on investment and land	$20 00
Interest on equipment	10 00
Preparation of land	10 00
Fertilizer	40 00
Plants	40 00
Setting plants	5 00
Cultivation	10 00
Picking 3,000 quarts at 2½ cents	75 00
Grading and packing at 1 cent	30 00
100 crates at 15 cents	15 00
3,000 boxes	11 00
Hauling to station	10 00
	$276 00

Southern U.S.; 1917

Interest on investment (land and equipment)	$8 00	to	$15 00
Preparation of land	5 00		10 00
Manure or fertilizer	10 00		25 00
Plants	10 00		20·00
Setting plants	8 00		12 00
Cultivating and hoeing	20 00		35 00
Mulching	15 00		25 00
Total for growing	$76 00	to	$142 00
Picking, grading, and packing 2,000 quarts	$40 00	to	$70 00
Crates and boxes	20 00		25 00
Hauling to station, loading, etc.	5 00		10 00
Total for picking, packing, grading, etc.	$65 00	to	$105 00
Total for growing	76 00		142 00
Grand total	$141 00	to	$247 00

Source: *Cyclopedia of Horticulture*, 1917

[173]Wicks, *Strawberry Growing in Arkansas*, p. 7.

[174]F. L. Thomsen and G. B. Thorne, *Economics of Strawberry Production and Marketing In Missouri*, pp. 41, 55, 138.

[175]Brannen and Dickey, *Strawberry Production and Marketing in Arkansas*, p. 24.

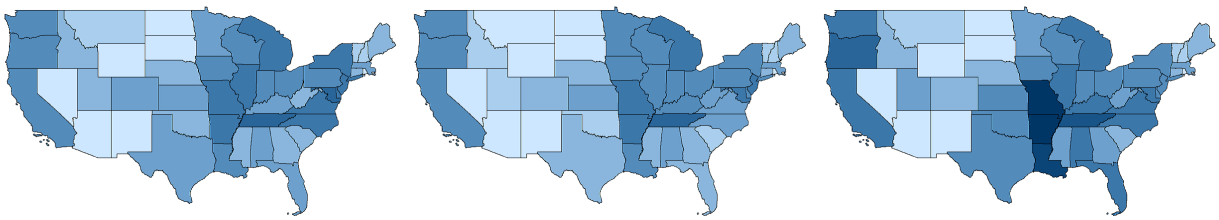
[176]Schilletter, Elwood, and Knowlton, *Changes in Technology and Labor Requirements*, pp. 6–7.

Aside from Louisiana, the Central South states invest considerably less than even the minimum indicated in Figure 3.9. Despite this, unit costs of production are not dramatically different; southern states range from approximately 7 to 12 cents per quart. As expected, Florida and Louisiana figures are very similar, although Louisiana is somewhat distorted by a precipitous decline in yields, which had fallen by over 50 percent between 1921 and 1925. It is entirely possible that this reduction had yet to be reflected in estimated expenditures.

An overview of state-level production is presented in Figures 3.9 through 3.11, illustrating how strawberry cultivation shifted to the south over the early 20$^{\text{th}}$ century. Eastern acreage and production were comparatively uniform throughout the first two decades of the 1900s; by 1930, the Central South had become the focal point of the industry, which had approximately doubled in size over the previous decade. Yields, however, appear to have been declining on a national scale. This may be evidence that extensive cultivation was representing a progressively larger share of production over time; it may also imply, perhaps simultaneously, that long-term issues with cultivation practices were not restricted to one region. Figure 3.11 is also noteworthy as it conveys California's unusually high productivity relative to the rest of the country. Despite advances in refrigeration, however, shipping to eastern markets was not yet feasible for most Californian growers.

Figure 3.10: **United States Strawberry Acreage (1000 acres)**

1909 1919 1929

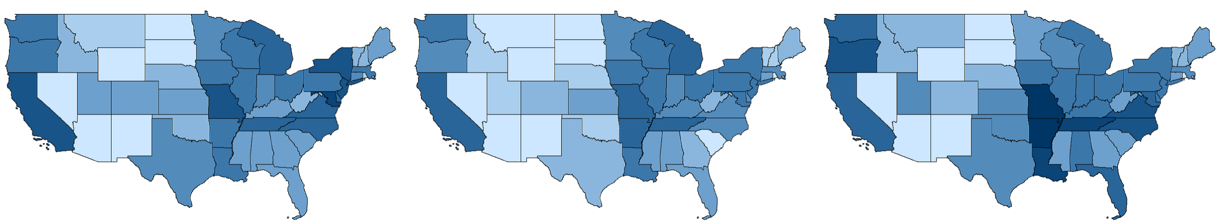


1909	1919	1929
Maximum: 14.3 (MD)	Maximum: 11.9 (TN)	Maximum: 27.3 (AR)
US Total: 143.0	US Total: 119.4	US Total: 242.8

Choropleth breaks (1000 acres): 0.25, 0.5, 1, 2.5, 5, 10, 15, 20, 25, 30.

Figure 3.11: **United States Strawberry Production (1000 tons)**

1909 1919 1929

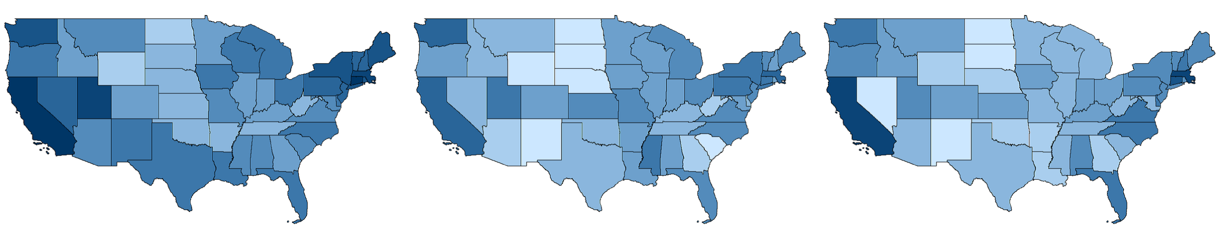


1909	1919	1929
Maximum: 23.6 (MD)	Maximum: 13.1 (TN)	Maximum: 27.6 (MO)
US Total: 255.7	US Total: 176.9	US Total: 330.9

Choropleth breaks (1000 tons): 0.25, 0.5, 1, 2.5, 5, 10, 15, 20, 25, 30.

Figure 3.12: **United States Strawberry Yield/Acre (tons)**

1909 1919 1929



1909	1919	1929
Maximum: 3.42 (CA)	Maximum: 2.2 (MA)	Maximum: 2.99 (CA)
US Average: 1.79	US Average: 1.48	US Average: 1.36

Choropleth breaks (tons/acre): 0.75, 1, 1.25, 1.5, 1.75, 2, 2.25, 2.5, 3, 3.5.
Source: United States Agricultural Census, 1909-1929.

Chapter 4

California Strawberries

Strawberry production in California can be traced back to the 1850s during the Gold Rush. Like the eastern states before them, early settlers in California relied entirely on wild strawberries, which grew abundantly along the coast. California's transition from gathering to harvesting, however, occurred far more rapidly than back east; by 1860, these new Californians had already begun cultivating promising selections of indigenous varieties. The transition from garden culture to commercial production was also considerably faster, as the critical pieces - transportation, improved cultivars, and pollination - were already established. Several of the strawberry varieties imported from the east thrived in California's climate, further accelerating the expansion of of the industry, though this also reduced incentives to develop local capacity for strawberry breeding.[1] This abbreviated period of development is analogous to the "leapfrogging" observed in agricultural sectors of developing countries, in which radical change occurs through the import of technology and cultural practices from developed countries.[2]

California's first commercial strawberry operations were established in the late 1850s near San Francisco and Oakland; the highly seasonal rainfall patterns restricted early cultivation to the coast, and San Francisco was both the primary market for growers as well as a hub for redistribution elsewhere in the state.[3] By 1860, production had reached 155 acres and average yields of about half a ton, and limited supply kept early prices at an average of 25 cents per pound.[4] Almost 90 percent of Alameda County acreage was dedicated to the "British Queen," a high-quality variety that had been discarded in the east because of its sensitivity to temperature.[5] Groundwater resources and the adoption of artificial irrigation allowed production to move further inland, with San Jose in particular noted for its "abundance of artesian wells most conveniently located for the culture of berries."[6] Santa Clara County as a whole expanded from 30 acres to 500 between 1857 and 1871, first rivalling, then supplanting Alameda as the center of strawberry production.[7] By 1875 San Francisco was supplied by

[1] Britton, "California Fruit Growers, Vol. 2", p. 13.
[2] Fong, "Technology Leapfrogging for Developing Countries".
[3] Flint, "California Culturist, Vol. 2", p. 294.
[4] Wadsworth, "California Culturist, Vol. 1", p. 73.
[5] Ibid., p. 73.
[6] Strentzel, "California Horticulturist, Vol. 8", p. 183.
[7] Bland, "Santa Clara County", p. 1.

berries "all raised in the Santa Clara Valley, within an area of about six miles."[8,9,10] One consequence of this increased supply: average prices fell to roughly 8 cents per pound, a third of what they had been in the 1850s.[11]

Commercial production was soon established outside of the immediate Bay Area. Farmers in the Pajaro Valley started cultivating strawberries in 1865, although early plantings were relatively small and their produce disposed of locally. The construction of new irrigation infrastructure between 1875 and 1880, including overflow flumes installed by Watsonville Waterworks, provided the means for the industry to flourish; acreage increased steadily from 1880 onward, from 42 acres to 268 in 1885, 522 acres in 1895, and 840 acres in 1902.[12] Growers anticipated even greater expansion following the construction of a coastal railroad, which would provide them a direct shipping route to Los Angeles.[13] The strawberry district of Florin, near Sacramento, experienced a similar pattern of development. The discovery of easily accessible groundwater led first to locally-oriented cultivation, then progressively greater investment in irrigation technology, and finally transition into a much larger shipping-oriented industry.[14] Between 1893 and 1903, production skyrocketed from 60 tons to "conservative estimate" of 1,900 on almost 1,000 acres, well on its way to "eclips[ing] all other fruit industries" in Florin. During the peak of the season, shippers estimated they sent 75 to 90 tons in a single day, 90 percent of which was sent to non-local markets.[15,16]

The strawberry industry of southern California developed towards the end of the 19$^{\text{th}}$ century, although local conditions were not as immediately hospitable. Farmers near Los Angeles began cultivating strawberries around the 1880s, but dealt with several early crop failures; issues included alkaline soil, poor planting stock, and difficulty adapting practices to the arid climate. The Wilson was one of the first varieties introduced to the region, but appears to have been unsatisfactory.[17] Research from the University of California's Pomona Field Station was instrumental to identifying and developing new varieties that were resistant to a combination of heat, drought, and sun damage.[18] The construction of two transcontinental railroads connected Los Angeles growers to distant markets, spurring further industry development; by 1899, the Tropico region had multiple strawberry farms 50 acres in size.[19,20] Growers in the El Cajon area, east of San Diego, began cultivating strawberries the 1890s, but imported eastern varieties failed commercially. This was attributed to "deficien[cies] in color and flavor," but it is unclear whether this was due to climate incompatibility, quality of the imports, or consumer taste.[21] The "Arizona Everbearing," or "Mexican" strawberry,

[8] Hooper, "California Horticulturist, Vol. 5", p. 389.
[9] Pacific Rural Press, "Strawberries in California", p. 326.
[10] Pacific Rural Press, "Large Strawberry Yield", p. 341.
[11] Pacific Rural Press, "Strawberries in California", p. 326.
[12] S. Wilhelm and James Sagen, *A History of the Strawberry*, pp. 174–178.
[13] Pacific Rural Press, "Strawberries in the Pajaro Valley", p. 181.
[14] Not Listed, "Florin is Naturally Adapted to Strawberry Culture", p. 6.
[15] Pacific Rural Press, "Small Fruit Figures from Florin", p. 341.
[16] Pacific Rural Press, "Agricultural Review", p. 315.
[17] Pacific Rural Press, "Strawberries in Southern California", p. 86.
[18] S. Wilhelm and James Sagen, *A History of the Strawberry*, pp. 179–180.
[19] Pacific Rural Press, "Strawberries in Southern California", p. 86.
[20] United States Senate Immigration Commission, *Immigrants in Industries*, p. 387.
[21] Pacific Rural Press, "Strawberry Growing in San Diego County", p. 84.

one of the varieties tested at the Pomona Station, was both drought-resistant and produced large, attractive fruit throughout the year. Unfortunately, it was too soft for shipping and thus relegated to local markets; by 1906, it was in the process of being phased out in favor of firmer varieties.[22] However, the research performed to develop this variety was credited with galvanizing the early San Diego industry, and demonstrated the value of the recently established Experiment Stations throughout the US.[23]

4.1 19th and Early 20th Century Production

Aside from market proximity, water was one of the largest contributors to agricultural land cost, and the necessity of irrigation made strawberry production an expensive undertaking. In the 1890s, it cost $30 to $100 to purchase a non-irrigated acre of farmland in Los Angeles County, and $100 to $200 for one with access to water; "ample" water rights and quality land could bring this cost up to $400. Alternatively, obtaining water from elsewhere cost growers between $2 and $12 per acre, per year.[24] The expense of the labor and capital required to set up irrigation - pumping, water conveyance, and land preparation - incentivized growers to maintain their plantings for several seasons. Strawberry beds were commonly kept for up to 8 years, and in some exceptional cases fruited for 12 years or more.[25] Eventually, the severity of pest pressure would necessitate shorter planting lifespans, particularly after the discovery of the virus xanthosis in the early 1910s. In 1917, the California Agricultural Experiment Station recommended the removal of plantations after no more than five years, and that plots where pests or diseases had taken hold should be plowed up and burned rather than remediated.[26]

Hill culture was the primary system of cultivation in the southern districts and along the Central Coast; further inland, near Sacramento, the matted row was more common. Strawberry plants were generally set in the fall; the removal of first-year blossoms was suggested, but appears to have fallen out of favor by the beginning of the 20th century.[27,28,29] Acreage tended to fluctuate as it brushed up against or exceeded the limits of in-state demand, causing strawberry districts to experience recurrent contractions and re-expansions. This behavior could be seen throughout the state, though the effects on individual districts were not uniform. At the turn of the century, close to 2,500 acres of strawberries were cultivated within 100 miles of San Francisco, with the majority of the estimated 5,000 tons produced sent to the city. In 1902, the *Pacific Rural Press* wrote that "prices have dropped early and the handlers in San Francisco appear to be in shape to fix prices so that they will get the cream of the profits."[30] In 1905, Pajaro Valley strawberry prices were higher than they had been for the past several years; one year later, strawberry acreage in Florin

[22] Pacific Rural Press, "Strawberries at the South", p. 146.
[23] Pacific Rural Press, "Strawberry Growing in Southern California", p. 312.
[24] Los Angeles Herald, "Matters Pertaining to Los Angeles, The Metropolis of Southern California", p. 4.
[25] Wickson, *California Fruits*, p. 490.
[26] Hendrickson, *Small Fruit Culture in California*, p. 15.
[27] Gillet, *Fragariculture*, p. 12.
[28] Pacific Rural Press, "Strawberry Growing in San Diego County", p. 84.
[29] Pacific Rural Press, "Strawberry Growing in Southern California", p. 312.
[30] Pacific Rural Press, "Larger Market Wanted For Berries", p. 315.

contracted by 25 percent, with a number of strawberry operations converted into vineyards as "it no longer figure[d] as a producer of berries."[31,32] The industry as a whole would enter yet another period of expansion in 1908, one which would come to a close at the beginning of the first World War.[33]

Irrigation

Edward Wickson, during his tenure as a horticultural lecturer at the University of California, wrote that "generous irrigation is the price of a long bearing season with the strawberry."[34] Irrigation was the fundamental difference between commercial plantings in California and the east, and added a new layer of complexity to production. The first step was to secure a source of water, which could be situated either above or below ground as well as on or off-tract. Surface water could be supplied via intake pipe, while groundwater necessitated drilling for wells; in both cases, costs scaled with greater pump capacity as well as distance.[35] Water would then need to be elevated; early irrigation was powered by windmills, which were subsequently replaced by steam and gasoline engines. As strawberries relied on frequent, small applications of water, pumping plants tended to be small as well. Annual water requirements for an acre were between 3 to 5 acre-feet - 1 to 1.5 million gallons - with individual applications averaging about a sixth of an acre-foot. A grower on light soils might irrigate once or twice a week in the summer, and once every ten to fourteen days in the spring and autumn; for heavy soils, a grower might irrigate about half as frequently. Different strawberry districts had their own local methods of irrigation: growers in the Pajaro Valley and in Florin tended to construct larger-capacity furrows and fill them rapidly, while those in Placer County or the San Fernando Valley would run smaller amounts of water for longer periods of time.[36] Recent literature on irrigation economics has emphasized potential efficiency gains from reducing water loss in both water conveyance and application (see Schoengold and Zilberman (2007), for example),[37] which can be observed in the ongoing changes in strawberry growers' choices of irrigation systems.

Assuming water was available, growers prepared the land for irrigation. The primary method adopted in California was furrow irrigation, which was amenable to existing cultivation methods; rows of strawberry plants were separated by simple trenches, or furrows, dug out by shovel, which were used to carry water from one end of the plot to the other. Furrows also served as paths for laborers when weeding the bed or picking fruit, avoiding potential root damage.[38] This form of irrigation encouraged the adoption of "raised bed" culture - strawberry rows were set on top of ridges of soil, which rose a few inches above level ground in order to allow water to spread laterally into the rows. This allowed for irrigation to travel down the bed without overflowing and injuring the plant or fruit.[39] Bed

[31] Pacific Rural Press, "Agricultural Review", p. 343.

[32] Pacific Rural Press, "Florin Strawberries", p. 87.

[33] Los Angeles Evening Herald, "$1000 Per Acre Net Profits in Strawberry", p. 10.

[34] Wickson, *California Fruits*, p. 486.

[35] Etcheverry, *The Selection and Cost of a Small Pumping Plant*, pp. 1–2.

[36] Hutchins, *Irrigation Practice in Growing Small Fruits in California*, pp. 26–30.

[37] Schoengold and Zilberman, "The Economics of Water, Irrigation, and Development".

[38] Gillet, *Fragariculture*, pp. 10–12.

[39] In contrast to raised bed culture, some growers adopted a "level" culture in which their strawberry rows were not elevated.

width depended on the soil type, which affected the rate water could percolate into the row; heavier, less porous soil meant slower movement and required narrower beds.[40] The number of furrows that could be irrigated at a single time depended on available water pressure and time constraints. Water was supplied via pumping plant and conveyed to a plot through a main irrigation conduit before being released into the furrows. Open wooden flumes were the most common, although simple earthen ditches and more expensive conduits of concrete or cast-iron were also used. Earthen ditches were the least expensive to construct but required more labor to operate; every time a farmer irrigated a row, the furrow had to be manually opened and then later re-dammed with soil. Water was also lost through seepage, adding to the cost of the operation. Metal and concrete were more durable and eliminated seepage, but their set up cost was double that of wooden flumes, restricting their installation to farms where another, more permanent crop would follow strawberries.[41] By 1883, growers had also started to experiment with "sub-irrigation," a method of slowly delivering water to rows of strawberries by allowing it to leach through porous, subsurface drain tiles, in effect a rudimentary form of present-day drip irrigation.[42]

In return for irrigation investment, growers enjoyed a bearing season two to four times longer than other strawberry producing regions. The typical season for northern California stretched from April until August, and in some microclimates small amounts of production could even occur through December. The local climate and the cultivar also determined yield patterns: strawberry plants might bear fruit in two or three large waves, or could instead be more evenly distributed throughout throughout the season.[43] Yields in the 1850s averaged a modest half-ton per acre, but increased substantially as growers adapted to their local growing conditions; by 1871 they would reach two to three tons, or very approximately 2,000 to 3,000 quarts.[44] Frost was a mild threat to production and could delay or damage early fruit, but the main bearing season was rarely impacted by poor weather. Even if rain disrupted picking, the length of the season ensured that a comparatively small part of the harvest might be lost.[45] Unfortunately, early irrigation methods also appear to have been taxing on both water supply and land quality. By the 1870s, farms in Santa Clara County were purportedly beginning to suffer from groundwater depletion and soil degradation, thought to be caused by excess irrigation washing away nutrients.[46]

Irrigation dictated many aspects of strawberry production. Flat land was preferentially cultivated because it allowed for relatively uniform distribution of water; if the incline was too great - more than one to two inches per 100 feet - the plot had to be leveled out, or "graded," prior to setting plants. Water collecting in low-lying areas, or "pooling," was also undesirable, and if sufficient water was available growers might flood their land to identify patches that needed to be filled. Hillside cultivation was more complicated and only practiced to an appreciable extent in the Pajaro Valley. Rows were set along the contours

However, this was not common.

[40] Hendrickson, *Small Fruit Culture in California*, p. 9.

[41] Hutchins, *Irrigation Practice in Growing Small Fruits in California*, pp. 2–10, 25–28.

[42] Pierce, "The American Garden, Vol. 5, No. 8", p. 145.

[43] Wickson, *California Fruits*, p. 486.

[44] Pacific Rural Press, "Strawberries in California", p. 326.

[45] McDowell, "The Economic Impact of Technology on Strawberries", p. 1786.

[46] Hooper, "California Horticulturist, Vol. 5", p. 228.

of the hill and graded more steeply to help direct water flow, which needed to be reduced in rate.[47] By the early 1900s, growers in Santa Clara and the Pajaro Valley had transitioned from shovels to horse-drawn "ridgers" and cultivators to save on labor costs of bed and furrow construction.[48] As growers accumulated experience with irrigation, they refined their methods and adapted them to local conditions. Soil composition, for example, affected the movement of water, which in turn affected ideal flow speeds, the necessary irrigation capital, and the maximum width of a strawberry bed. In cases where the soil was too dense to absorb water quickly enough, small wooden or soil dams were placed in the furrow, slowing irrigation flow and preventing flooding.[49] In Florin, early irrigation was often insufficient during the hot summers, resulting in stunted plants and lost production. Over time, local farmers increased their furrow depth, helping to conserve moisture and hastening lateral percolation into the strawberry beds by increasing the surface area.[50] Excess irrigation was also detrimental, as water could rise above the strawberry bed and injure the fruit It was also associated with outbreaks of "rust," a fungal disease that could could be transmitted between leaves via contact with water. Some early operations in Santa Clara constructed irrigation furrows up to a quarter-mile in length, which impeded their ability to deliver water evenly.[51] By the early 1900s, the average furrow in Santa Clara was reduced to just 200 or 300 feet, affording more precise control.[52]

Sharecropping

Another distinguishing feature of California strawberry production was an unusual preponderance of sharecropping. Common arrangements assigned tenants the responsibility for cultivation, harvesting, and packing, while landlords furnished the plants, chests, and land preparation.[53] Leases might also include loans for first-year provisions, some or all of the necessary water, and potentially room and board.[54] In cases where a landlord struggled to lease out their land, they might also provide funds for a tenant's personal use. The gross proceeds of an operation were usually evenly split between the parties; while possible allowances were sometimes made if this division failed to cover the costs of production, this meant that the tenant still absorbed the economic brunt of a poor season.[55,56]

Sharecropping in the strawberry industry was linked to the intensity of cultivation and overall scarcity of agricultural labor.[57] Labor supply was as critical as water availability; an individual worker could maintain up to two acres on their own, but an additional six or more were required during harvest season.[58] California strawberry farms also appear to have been relatively large, as principal growers in the Santa Clara Valley cultivated between

[47]Wickson, *California Fruits*, pp. 486–488.

[48]Hutchins, *Irrigation Practice in Growing Small Fruits in California*, pp. 2–4, 12–15.

[49]Ibid., pp. 2–4, 12–15.

[50]Not Listed, "Florin is Naturally Adapted to Strawberry Culture", p. 6.

[51]Wilcox, "California Fruit Growers, Vol. 6", pp. 230–232.

[52]Hutchins, *Irrigation Practice in Growing Small Fruits in California*, p. 18.

[53]United States Senate Immigration Commission, *Immigrants in Industries*, p. 405.

[54]Pacific Rural Press, "Strawberries in California", p. 326.

[55]Pacific Rural Press, "Prices for Strawberry Fields", p. 232.

[56]Pacific Rural Press, "Strawberries in California", p. 326.

[57]Olmstead and Rhode, "Evolution of California Agriculture", pp. 1–5.

[58]Pacific Rural Press, "Strawberries in California", p. 325.

20 and 25 acres. Some particularly extensive growers were reported to cultivate anywhere from 50 to 100 acres, although this appears to have been uncommon, and may have been a single landowner leasing segments of their fields to different tenants.[59] In general, agricultural districts in California lacked sufficient employment opportunities to retain and support the necessary population of seasonal workers permanently.[60] Strawberries themselves were at the upper end of labor-hour requirements per acre, and reports of short-term labor deficiencies during the harvest season were not uncommon.[61] A significant fraction of agricultural workers were thus migratory, moving from region to region as local industries hit peak labor demand. This created a second form of labor instability: if other crops were ripening and higher wages were anticipated, laborers would move on, especially if most of the strawberry crop - and therefore their income - had already been picked.[62]

Strawberry sharecropping in California came to rely on a workforce comprised of recent Chinese immigrants, who had been forced into the agricultural sector as a result of dwindling employment opportunities along with legal and economic discrimination.[63] Over the 1860s and 1870s, many of these immigrants wound up gravitating towards strawberry tenancy; profits were relatively high and limited capital and access to credit were not severe liabilities, and tenant farming defrayed the high cost of land. Others joined contractual labor companies and organized into a “gang” system; these companies served as both point of contact and labor distributor, sending out groups of workers to agricultural communities as needed.[64] As hired hands, Chinese immigrants’ wages were roughly half that of domestic labor, and living conditions on farms tended to be poorer.[65] If their employer was not also Chinese, board was rarely included, and lodgings were substandard if they were provided at all; gang organizers often stepped in to provide these services to their workers at cost.[66] For landowners, the lower cost of Chinese immigrant labor and the convenience of the gang system were vital. By the 1870s, an estimated 10,000 Chinese laborers, approximately 15 to 20 percent of the total Chinese population in California, were annually employed as either strawberry sharecroppers or seasonal help, comprising the overwhelming majority of all labor in the industry.[67,68]

Chinese workers comprised nearly all of the labor force of the strawberry industry, before they were displaced by a combination of racial animus, rising wages, and population attrition following the Chinese Exclusion Act of 1882. Their position was eventually inherited by more recent Japanese immigrants, who had been migrating to California in growing numbers since the late 1880s. Low strawberry prices and a gradual loss of available labor had actually caused important districts to undergo acreage contractions over the 1890s, which presented a profitable opportunity for new, capital-poor arrivals; Japanese immigrants would go on to extend production significantly, adopting the same model of tenant arrangements and

[59] Hooper, “California Horticulturist, Vol. 7”, pp. 139–140.

[60] United States Senate Immigration Commission, *Immigrants in Industries*, pp. 14–15.

[61] Pacific Rural Press, “The Curse of the Day”, p. 364.

[62] United States Senate Immigration Commission, *Immigrants in Industries*, p. 242.

[63] P. S. Taylor and Vasey, *California Farm Labor*, p. 9.

[64] United States Senate Immigration Commission, *Immigrants in Industries*, pp. 17–19.

[65] F., “California Culturist, Vol. 3”, p. 18.

[66] United States Senate Immigration Commission, *Immigrants in Industries*, pp. 17–25.

[67] Pacific Rural Press, “Strawberry Growing in California”, p. 227.

[68] P. S. Taylor and Vasey, *California Farm Labor*, p. 9.

gang system organization as Chinese immigrants before them. This created a second wave of overproduction and low prices - Florin, for example, expanded from 240 acres in 1899 to 1,020 in 1904, only to contract to 540 by 1907.[69] Regardless, Japanese immigrants continued to enter the strawberry industry; by 1910, they and their children were responsible for nearly all of the strawberry production within the state.[70,71]

4.1.1 California Fruit Production Trends

In the first chapter of *California Agriculture: Dimensions and Issues*, Alan Olmstead and Paul Rhode discuss the role of credit in California's transition from grain production to specialty crops during the latter half of the 19th century. Despite the potential profit from relatively intensive crops, such as fruit trees and vines, the absence of a robust financial market was a serious hurdle to farmers looking to enter production. Fruit trees required several years before coming into bearing, and prevailing interest rates - over 100 percent during the Gold Rush - effectively barred farmers from making long-term investments. As these rates declined over the next several decades, a progressively greater amount of land was converted from grain into horticultural crops, ushering in the development of downstream industries like processing and transportation.[72]

Newly-available credit, along with the profit speculation associated with limited supplies, fueled the expansion of fruit culture in California. Production soon outpaced demand, and prices fell across the board as markets were unable to absorb the surplus. In particularly abundant seasons, fruit sold so cheaply that farmers struggled to cover costs, and leftover produce was fed to livestock or simply thrown away.[73] In 1871, E.J. Hooper of *The California Horticulturist* lamented that:

> "Unless at convenient distances from the great markets, the production of many, perhaps we may say most, of the fruits has been overdone, the prices not justifying their being carried to market. Millions of bushels annually rot on the ground."[74]

There is qualitative evidence that overlapping bearing seasons for horticultural crops - many of which ripened during the summer - put further downward pressure on prices through substitution effects.[75,76] Fruit growers were advised to practice "mixed husbandry," limiting the production of any single crop to reduce risk and spread out their income.[77]

[69] United States Senate Immigration Commission, *Immigrants in Industries*, p. 403.
[70] Ibid., pp. 26–32, 104–106, 387.
[71] Pacific Rural Press, "Agricultural Notes", p. 237.
[72] Olmstead and Rhode, "Evolution of California Agriculture", pp. 3–7.
[73] Strentzel, "California Horticulturist, Vol. 8", pp. 232–233.
[74] Hooper, "California Horticulturist, Vol. 1", p. 330.
[75] Hooper, "California Horticulturist, Vol. 6", p. 132.
[76] Not Listed, "California Horticulturist, Vol. 4", p. 121.
[77] Pacific Rural Press, "Variety in Fruit Culture", p. 308.

Fruit Processing

Profitable disposal of excess fruit had become a pressing issue for virtually all horticultural producers. They began to search for ways to profitably ship fruit to markets outside of California, which presented opportunities to leverage comparative advantages in productivity and season length. Experimental long-distance shipping of fresh produce in the 1870s and 1880s demonstrated that it was technically feasible, and that external markets were indeed able to absorb a great deal of California production; however, early results were often disappointing in practice, as improper packing and handling of soft fruits was pervasive and took years to rectify.[78] Fruit processing - canning more so than drying - became an important secondary outlet for agricultural surplus, in part because these products could be readily shipped to distant markets without fear of spoilage.[79] Processing also offered farmers an important measure of income stability; while processors paid less on average than the fresh market, they usually took on the farmer's supply and demand-side risk through flat-rate production contracts.[80] By 1877, Alden "drying-houses" could be found in Riverside, Santa Rosa, and Auburn, and at least nine canning operations were put into operation; a single facility in San Jose accounted for half a million cans of fruit annually, and another several thousand tons were processed in Amador and El Dorado Counties.[81,82,83]

The canning industry in particular grew steadily throughout the end of the 19th and into the 20th century. Between 1890 and 1905, it had had risen from the seventh to the second most important manufacturing industry in California; its annual output was valued at almost $24 million, with a total capital investment of $9.3 million. The number of canning establishments had increased to 167, and were estimated to employ over 7,000 people; for the majority, cannery work was seasonal and irregular, with the highest labor demand occurring at peak harvest seasons. Depending on the location, fresh market prices, and what crops were being canned, these facilities were in operation between two to seven months at a time.[84]

Associations in California

California's geographic isolation posed both a technological hurdle as well as a financial burden to growers; fresh produce could be shipped by ventilator car to adjacent states and the Pacific Northwest, but all other markets required the use of refrigerator cars, with all of their attendant costs further compounded by the high rates of long-distance shipping.[85,86] In the 1870s and 1880s, numerous cooperatives were organized for the purpose of "marketing fruits to the best advantage"[87] - this included lowering the cost of freight, improving produce handling methods, coordinating shipping to prevent overstock, and promoting greater fruit

[78] Gardner, *Beginnings of Cooperative Fruit and Vegetable Marketing*, p. 5.

[79] Strentzel, "California Horticulturist, Vol. 8", p. 233.

[80] Not Listed, "California Horticulturist, Vol. 4", p. 118.

[81] Hooper, "California Horticulturist, Vol. 7", p. 100.

[82] Hooper, "California Horticulturist, Vol. 7", p. 22.

[83] Hooper, "California Horticulturist, Vol. 8", p. 309.

[84] United States Senate Immigration Commission, *Immigrants in Industries*, pp. 247–249.

[85] C.M., "The Fruit Growing Interest", p. 324.

[86] Rudisill, "California Horticulturist, Vol. 10", p. 70.

[87] Pacific Rural Press, "Fruit-Growers' Union", p. 363.

consumption outside of California.[88] The first statewide association, the California Fruit Union, collapsed within ten years as a result of internal conflict and freeriding.[89] Smaller associations at the local and regional level met with varying degrees of success, although their overall influence over freight costs appears to have been relatively weak; in 1901, a speaker at the California Fruit-Growers Convention reported that charges that Oregon farmers paid for refrigerated car shipments to points east were 50 to 70 percent lower than in California, which he attributed to their well-funded state horticultural society.[90] The processing industry achieved a measure of success by carving out a niche in the "high end" of markets, differentiating their products from American and European competitors with an emphasis on fruit quality and superior shipping and packing methods.[91] With time, this quality differential extended to fresh produce and generated similar results. In 1901, a paper from Spain claimed that their producers were being pushed out of European markets, as California fruits and vegetables were "reach[ing] Paris, after traversing 6,000 miles, in a more attractive and appetizing condition than ours after a journey of only 490 miles."[92] Fruit exports continued to climb through the 19th and into the 20th century. One estimate for the 1876 season placed the total weight of shipments at roughly 6.5 million pounds; in 1895, at least 100 million;[93] in 1900, 150 million.[94,95]

Like the South, California's strawberry industry also stood to benefit immensely from both grower coordination and a new outlet for surplus production. By prioritizing urban centers as their primary markets, growers had simultaneously depressed prices and left smaller, still profitable markets to be supplied by middlemen.[96] There were mounting concerns over the strawberry business being "overdone;" unusually high yields caused strawberries to bottom out at 3 cents per pound, and farmers abandoned over a third of the vines in the Santa Clara Valley.[97] Several local and regional associations of berry growers began to form around the same time as the broader fruit cooperatives: farmers in San Jose had organized no later than 1877, those in Salinas Valley by 1895, in Pajaro Valley by 1899, and around the Central Coast by 1917.[98,99] Aside from cargo pooling and negotiations with railroads, some associations pooled their members' resources to build farmer-owned canneries. Others made arrangements with commission houses, directing all of their production to specific merchants in return for better prices. The Watsonville association attempted to stabilize the market directly; members signed an agreement to use specific commission houses and to obtain flat prices for their shipments, and a committee was appointed to estimate expected acreage and yields for the upcoming season.[100,101]

[88] Pacific Rural Press, "The Fruit Problem", p. 363.
[89] Gardner, *Beginnings of Cooperative Fruit and Vegetable Marketing*, pp. 5–8.
[90] Stephens and Judd, "California Fruit Growers, Vol. 26", p. 168.
[91] Olmstead and Rhode, "Evolution of California Agriculture", p. 22.
[92] Phelan, "California Fruit Growers, Vol. 26", p. 6.
[93] This assumes minimum weight carloads of 24,000 pounds.
[94] Strentzel, "California Horticulturist, Vol. 8", pp. 263–264.
[95] Weinstock, "California Fruit Growers, Vol. 26", p. 16.
[96] The California Farmer, "Is the Small Fruit Business Overdone?", p. 3.
[97] Pacific Rural Press, "Agricultural Notes", p. 357.
[98] Pacific Rural Press, "Untitled", p. 1.
[99] San Jose Herald, "The Strawberry Growers", p. 3.
[100] Pacific Rural Press, "Cooperation Among Strawberry Growers", p. 231.
[101] Pacific Rural Press, "Agricultural Review", p. 138.

Geographic isolation and the strawberry's adaptability to various climates did not lend themselves well to opening up markets outside of California. In an address to the 1905 California Fruit-Growers Convention, then-Governor Pardee divided the state's horticultural exports into three "lines" of production - those where California held a monopoly, others where it held a significant competitive advantage, and finally those where California was on even footing with other producers.[102] Strawberries fell somewhere between the last two categories; California's higher yields notwithstanding, almost every state had some amount of local production. There was significant overlap with production from other states until midway through the season, after which other fruits were available, with proportionally lower freight costs tacked on to the final price.[103] Although cross-continental shipping had become technically feasible, it remained impractical as profits were typically too low to justify the cost. Aside from competition, transportation and duration of transit were limitations on the strawberry industry, especially when targeting smaller markets that depended on re-shipments of fruit from larger hubs. In 1901, early season railway service to Chicago took six to seven days, and cities on the Atlantic seaboard from ten to eleven; as the season progressed, an extra two to three days of travel time were added to both of these routes. According to the president of the California Fruit Growers and Shippers' Association, these delays put a variety of fruits on the cusp of becoming unmarketable, forcing them to be sold at point of arrival; while strawberries were not part of the shipments in question, it is unlikely they would have fared better.[104]

Although canning strawberries eliminated spoilage, high costs meant that processors were still largely restricted to markets in California, as local and regional processors in the east faced lower costs of materials, labor, and transportation.[105] and California growers were unwilling to sell strawberries at prices low enough to make competition viable, preferring to take their chances in the fresh market; in 1881, an article in the San Jose *Morning Times* argued that Santa Clara strawberries were unjustifiably expensive, impeding the development of a local canning industry and risking a market glut in San Francisco.[106] Two decades later, in 1903, only 125 of the nearly 1,900 tons of strawberries produced by Florin growers were contracted for by canneries.[107] In 1905, the *Pacific Rural Press* reported that two farmers in the Pajaro Valley had contracted their entire crop to processors, but that many others preferred "to handle them on their own responsibility."[108] Central California growers would only begin shipping processed strawberries to eastern markets in 1921.[109] Even so, a 1922 article in the *Rural Press* dismissed the possibility of a Stanislaus County cannery securing local production; according to the author, the Central California Berry Growers' Association considered it "bad business to try and make a success of berry growing on cannery prices."[110] Processing in California continued to serve as a distress outlet for surplus strawberry production until the late 1940s, when household demand for frozen goods began

[102]G. Pardee, "California Fruit Growers, Vol. 31", pp. 15–16.
[103]Thomas, *The Production of Strawberries in California*, pp. 90–91.
[104]Weinstock, "California Fruit Growers, Vol. 26", pp. 14–15.
[105]Pacific Rural Press, "Small Fruits Commercially Considered", p. 542.
[106]The Morning Times, "Canning Interests", p. 1.
[107]Pacific Rural Press, "Small Fruit Figures from Florin", p. 342.
[108]Pacific Rural Press, "Agricultural Review", p. 343.
[109]Pacific Rural Press, "Production Stifled by Railroad Rates", p. 697.
[110]Pacific Rural Press, "Strawberries in North San Joaquin", p. 580.

to flourish.

4.2 Economics of Production in California

Prices: Higher production volumes in California towards the end of the 19th century had brought prices down considerably. Short-term price volatility remained highly pronounced, and growers' resilience to market changes was compromised by their lack of crop diversity.[111] Volatility would start to diminish in the early 20th century as supply became more uniform - a result of cooperative shipment coordination and new transportation infrastructure. This can be seen in Tables 4.1 and 4.2 below:

Table 4.1: **Wholesale Prices of Strawberries; San Francisco, 1870s**

Year	March	April	May	June	July
1872	No sales rec.	15-40 c/lb	10-15 c/lb	12.5-15 c/lb	8-12 c/lb
1873	$0.75-1.50/lb	7-45 c/lb	5-15 c/lb	5-15 c/lb	3-9 c/lb
1875	$2.00-2.50/lb	25-30 c/lb	10-25 c/lb	15-25 c/lb	10-23 c/lb
1876	No sales rec.	13-15 c/lb	9-15 c/lb	No data	5-10 c/lb
1878	$0.50-2.00/lb	9-35 c/lb	7-10 c/lb	5-11 c/lb	3-5 c/lb
1879	No sales rec.	5-20 c/lb	3-10 c/lb	5-25 c/lb	6-12.5 c/lb

Table 4.2: **Wholesale Prices of Strawberries; San Francisco, 1900s**

Year	March	April	May	June	July
1900	7-13 c/lb	3-7 c/lb	5-7.5 c/lb	3-7.5 c/lb	3-5 c/lb
1901	No sales rec.	7.5-9 c/lb	5-15 c/lb	5-7.5 c/lb	4-5.5 c/lb
1903	No sales rec.	6-15 c/lb	5-9 c/lb	3-6 c/lb	2.5-5 c/lb
1904	No sales rec.	6-10 c/lb	2.5-9 c/lb	2.5-6 c/lb	2.5-6 c/lb
1905	No sales rec.	4-9 c/lb	3-9 c/lb	4-10 c/lb	2.5-6 c/lb
1908	6-8 c/lb	9-19 c/lb	6-17.5 c/lb	5-10 c/lb	2.5-7 c/lb
1909	No sales rec.	4-10 c/lb	4-9 c/lb	4-7.5 c/lb	2.5-5 c/lb

Sources: *California Horticulturist* and *Pacific Rural Press* market reports.
Ranges are based on monthly minimum/maximum prices (data permitting). Specialized varieties excluded.

These tables also show that strawberries from Los Angeles were available in San Francisco as early as March; reports also show small quantities were occasionally sold in February. The frequent gaps in market report price data imply that these shipments were somewhat irregular, but from the prices recorded in Table 4.1 the returns on early strawberries could be an order of magnitude greater than in the following months. The price premium for early

[111] United States Senate Immigration Commission, *Immigrants in Industries*, p. 309.

production seems to have diminished in the early 20th century, although market reports also suggest these prices were unusually low due to inferior produce. According to a report by the Immigration Commission, growth of strawberry acreage under Japanese tenants had caused prices to decline post-1904, eventually "breaking" in several regions within California following the 1908 season.[112] This is not immediately apparent from San Francisco records, but processing facilities may have played a role; several market reports from the 1909 and 1910 seasons indicate diversion of larger-than-average quantities of strawberries to syrup and canning. Costs of production were usually too high for processing to be used as anything more than a safety valve, but reported contracts imply the price floor they provided was roughly $3 to $4 per chest, or 3 to 5 cents per pound.[113]

Yields and Profits: Estimates in the Agricultural Census of California strawberry yields ranged from 2 to 3 tons per acre during the late 19th century, and would approach 3 to 4 tons in the first decade of the 20th. Newspaper interviews with growers suggest average profits remained fairly consistent over the 19th century, ranging from $100 to $300 prior to division between land owner and tenant.[114,115] This compared favorably with staple crops, which brought in $25 to $50 per acre, albeit with lower costs of production. Acreage and profits, as usual, were cyclical; farmers entered production when prices were high, until increased production depressed prices and pushed them back out. In an article to the *Pajaronian*, a Watsonville farmer estimated that his annual net returns over 1894 to 1899 amounted to just $23 per acre. The editor of the paper concluded that "strawberry growing is not a very profitable business — in fact, that there are other crops which involve less of labor and investment and which assure better profits."[116] Profits were also highly variable; in a 1908 sample of Pajaro Valley tenant farmers - over 90 percent of which were exclusively strawberry growers - 27 percent reported either breaking even or accruing debt over the season, while 18 percent saw profits of at least $500.[117]

Contracts and Labor: Although there were some individual variations, the usual sharecropping arrangement split the sales evenly between the parties, with the majority of the labor supplied by the tenant. By the early 1900s, a contract system was also employed; instead of being paid with half of the harvest, tenants were paid a flat rate per chest of strawberries sold. Contract payment was roughly $1.50 to $1.75 per chest, or 2 to 2.5 cents per pound. They were also compensated for bringing more land under cultivation, but penalized if they neglected picking or failed to hire sufficient workers. Cash rental also became more common in the early 1900s; these farmers were essentially independent, with some limited oversight regarding crop choice and maintaining the property. Some landlords with previously uncultivated acreage also adopted an "orchard lease" - tenants would clear the land and assist the owner in establishing fruit trees in lieu of paying rent.[118] Temporary workers were paid piece rates or a daily wage. In the 1870s, a Santa Clara newspaper estimated

[112] United States Senate Immigration Commission, *Immigrants in Industries*, pp. 403–404, 441.
[113] S. Wilhelm and James Sagen, *A History of the Strawberry*, p. 178.
[114] Pacific Rural Press, "Strawberries in California", p. 326.
[115] United States Senate Immigration Commission, *Immigrants in Industries*, p. 407.
[116] Pacific Rural Press, "Cost and Profit on Strawberries", p. 68.
[117] United States Senate Immigration Commission, *Immigrants in Industries*, p. 441.
[118] Ibid., pp. 422–439.

the overall cost of harvesting and shipping at roughly three cents per quart; per-pound costs of freight, hauling, and picking were $\frac{1}{2}$, $\frac{1}{4}$, and 2 cents respectively.[119] These prices appear to have remained largely consistent even into the 1930s.[120] Wages for strawberry pickers were approximately $1.50 daily, with some variation - 10 to 20 cents in either direction - based on length of day and whether they were provided with room and/or board.[121]

Land Rental: Although trends in land price are somewhat obfuscated by the use of share-cropping, publications in the late 19th century suggest leases ranged from $5 to $25 per acre.[122],[123] Cash rentals would become more common by the early 1900s, and rental rates were generally comparable. In 1910, farmland in the Los Angeles Area was leased at $15 to $30 per acre, depending on locality; the Pajaro Valley, for $15 to $25 an acre; Alviso, $10 to $20; and Florin, between $30 and $100, averaging $40.[124] Rates appear to have remained consistent for the next few decades; in the late 1930s, a survey of 98 renters found that strawberry leases varied from $12.50 to $65 an acre.[125]

Land Preparation: In an irrigation bulletin from 1916, Wells Hutchins of the California Agricultural Experiment Station provided a detailed discussion of the steps involved in preparing land for strawberry cultivation, as well as the associated costs. The following estimates are derived almost entirely from his work.[126]

- **Surveying**: Future irrigation channels were demarcated with stakes every 50 to 100 feet prior to their construction/excavation. The overall design was intended minimize the amount of grading required; the main flume was set at the highest edge of the plot, and the positions and angles of secondary channels and furrows were influenced by its contours. Surveying cost between $2 to $2.50 per acre depending on the topography.

- **Setting, Plowing, Cultivating**: Commercially grown strawberry varieties typically cost between $2 and $6 per thousand plants, although they could reach upwards of $15 or $20 depending on the variety. An acre was set with anywhere between 12,000 and 20,000 plants. The cost of setting the plants was roughly $8 to $10 per acre, while the plants themselves cost $20 to $50 per acre; bulk purchases of transplants were discounted, and expensive varieties were more likely to be grown under intensive culture and thus afforded more space.

- **Leveling, Furrows**: Topography determined capital requirements for grading the plot. When a comparatively small amount of soil was to be moved, a berry "leveler" - a wide wooden board of adjustable height, mounted on wheels - was run between surveying stakes to even out the plot. Uneven ground required more soil redistribution; growers would first use a "Fresno scraper" - a bulldozer-like implement pulled by horses

[119] Pacific Rural Press, "Strawberries in California", p. 326.
[120] Thomas, *The Production of Strawberries in California*, p. 24.
[121] United States Senate Immigration Commission, *Immigrants in Industries*, pp. 421–422.
[122] Hooper, "California Horticulturist, Vol. 1", p. 330.
[123] Pacific Rural Press, "Cost and Profit on Strawberries", p. 68.
[124] United States Senate Immigration Commission, *Immigrants in Industries*, pp. 388–405, 440–446.
[125] Adams and W. H. S. Jr., *Farm Tenancy in California and Methods of Leasing*, p. 83.
[126] Hutchins, *Irrigation Practice in Growing Small Fruits in California.*

- before following up with the berry leveler. If water was sufficient, the acre would be flooded post-leveling to identify any depressions that needed to be filled. The cost of leveling varied substantially, ranging from $4 to $40 based on the amount of soil moved and possibly with the precision of the grade. After grading, furrows were shoveled out, either by hand or a horse-drawn scraper, and the lower end fed into a drainage channel. Handwork offered greater precision for furrow alignment, but cost $15 per acre compared to $6 or $7 for horses. Leveling the soil also encouraged extensive cultivation to make it easier to move, costing an additional $5 to $10 per acre.

- **Conduits**: Irrigation conduit materials were chosen based on anticipated future crop choices as well as the availability (and thus pricing) of water. Earthen ditches ran from $2 to $3 per acre, but could lose up to 60 percent of diverted water to seepage depending on length and soil type. Ditches would also erode over time, requiring periodic reconstruction. Wooden flumes cost $15 to $20 per acre depending on their design; growers could economize on materials if the required water flow was small, and paid extra for any trestlework necessary to cross low areas or depressions. Compared to ditches, flumes were more robust and substantially reduced seepage losses, but were still subject to deterioration. They required repairs and maintenance after two or three years, and often needed to be completely replaced after eight or ten. Concrete or iron piping was superior to wood in both lifespan and prevention of leakage, but was also twice as expensive to set up - roughly $30 to $40. For all conduits, greater distance from a pumping plant or surface water source proportionally increased construction costs.

Irrigation and Pumping: According to the California Experiment Station, the total cost of installation for a "well-constructed" gravity-fed irrigation system was at least $50 to $60 per acre in the early 1900s, with annual operating expenses of $2 to $5 per acre. However, agricultural demand for water had also begun to outstrip existing gravity-fed supply;

> "Except in southern California up to a few years ago gravity water obtainable without pumping has been available... and comparatively few pumping plants have been constructed. However... water has become sufficiently valuable to justify pumping."[127]

Assuming a grower operated a private plant, installation could cost anywhere from several hundred to a few thousand dollars depending on size, fuel source and the required elevation (or "lift").[128] A pump might be powered either by a windmill or a motor fueled by gasoline, steam, or electricity; this choice was governed by intended size, flow rate, and lift. Electricity, if available, was both cheaper to install and required less attendance and maintenance than either gasoline or steam, a cost advantage which outweighed the increased expenditure on fuel. Windmills were less expensive than engine power, but were limited to smaller plots even where wind was reliable.[129] Pump capacity varied from district to district based on

[127] Etcheverry, *The Selection and Cost of a Small Pumping Plant*, p. 29.
[128] Ibid., pp. 1–4, 28–30.
[129] Pacific Rural Press, "How Much Will a Windmill Irrigate?", p. 136.

irrigation practices and soil type, and could vary from 30 to 300 gallons per minute.[130] Tapping groundwater resource required boring wells and additional lift, increasing costs over surface water pumps. Secondary elements could also affect costs; farmers could cooperate to reduce pumping expenses through greater investment in a single, larger plant, reducing installation and operation costs and improving efficiency. The expected lifetime of a gasoline engine was roughly a decade; an electric motor, between 15 to 20 years. Operating cost to supply an acre-foot of water could vary anywhere between $10 and $20 annually; annual depreciation was estimated at roughly 5 to 8 percent of the initial cost, and maintenance an additional 1 to 3 percent.

Bernard Etcheverry, prior to his tenure at the University of California, estimated sample costs for a pumping plant and its operation reprinted below in Figure 4.1.

Figure 4.1: **Costs for Irrigation Plant (gasoline motor), 1914**.

First Cost of Plant

No. 3 centrifugal pump	$57.00
7 horsepower gasoline engine	450.00
Priming pump, suction pipe, fittings, etc.	50.00
Freight charges and hauling	30.00
Wood-banded discharge pipe, 200 ft. of 4 in.	40.00
Installation, 5 per cent of cost	35.00
Building to house plant	40.00
Total cost	$702.00

Total Annual Cost of Operation

Fuel cost of 7 brake horsepower engine for 3 periods of 10 days each or 720 hours = 720 × 7 × 1.33 = 67,032	$67.03
Fixed charges at 17 per cent of first cost	120.00
Attendance 720 hours at 10 cents	72.00
Total cost for 20 acres	$259.03
Cost per acre, $12.95.	

Alternatively, if electricity was available:

First cost of plant	$375.00
Total cost of operation (annual)	215.00
Cost of operation per acre	11.00

Source: Etcheverry, *Irrigation*, 1914.

It is important to note that costs of installation and operation depended on a number of specifics. Etcheverry's hypothetical plant was designed to use surface water to irrigate a 20-acre orchard; required lift was assumed to be 50 feet, and the plant was expected to draw a total of ten acre-feet of water over the course of a month.[131] Assuming 10 days of

[130] Hutchins, *Irrigation Practice in Growing Small Fruits in California*, pp. 26–30.

[131] An "acre-foot" is a unit of measurement equivalent to 43,560 cubic feet, or the quantity necessary to cover an acre in one foot of water.

operation each month, the pump needed to be capable of moving 225 gallons per minute. Greater lift, acreage, or irrigation requirements would necessarily increase variable and fixed costs; increasing plant uptime would allow for smaller capacity pumps, though it would also increase fuel costs and the frequency of inspections.

With respect to strawberries, estimates of farmers' typical expenditures on irrigation plants are not readily available. Etcheverry's plant would supply only 30 to 60 percent of the total water needed for a grower of the same acreage. However, it would also supply this water over a shorter duration and with a flow rate at the upper end of the spectrum. We might surmise from these specifications that a pumping plant for strawberries might have lower fixed costs - provided they used a smaller pump and engine - but annual operating costs would be potentially higher given the longer period of operation and the decrease in fuel efficiency from the smaller engine.

Cost Summary: Experiment station estimates, summarized in Table 4.3, notably span a wide range of cultivation practices and assumed yields. Higher expenses are representative of the Central Coast and southern California, and the lower with the interior valley districts.

Table 4.3: **Costs of Production, 1939**

Item	Annual Expenses (per acre)	
	First Year	Subsequent Years
Rent	$10-$45	$10-$45
Grading/Leveling	$20-$45	
Land Preparation	$5-$10	
Plants	$14-$85	
Setting Plants	$15-$35	
Flumes	$0-$45	
Cultivation and Care	$60-$200	$25-$75
Water	$10-$30	$15-$50
Sprays/Dust	$0-$10	$0-$20
Fertilizer	$0-$20	$0-$30
Worker Housing	$0-$35	$0-$35
Well/Pump/Motor	$0-$75	$0-$75
Transportation		$50-$155
Baskets		$60-$180
Picking		$135-$405
Depreciation	$5-$50	$5-$50
Total	$139-$685	$300-$1,200

Source: Thomas, *The Production of Strawberries in California*, 1939.

It is important to emphasize that these costs are only intended to be illustrative, as they were known to change dramatically; in 1939, the California Experiment Station noted that "any attempt to predict future costs [was] particularly hazardous."[132] Most of the services

[132] Thomas, *The Production of Strawberries in California*, p. 23.

included here would be rented by growers with limited acreage, who otherwise would have been unable to justify the capital outlay. Additionally, the cost of wells and housing are assumed to be maintenance of existing capital, not construction.

4.3 California in the Prewar Era

California strawberry acreage increased slowly but steadily through the 1920s and 1930s, eventually peaking at slightly more than 6,000 acres in 1941. The farm value of production, on the other hand, fell from $4 million in 1927 to $2 million in 1932, a result of declining prices and stagnating productivity. National per capita consumption of fresh strawberries decreased 17 percent between the 1920s and 1930s, the beginning of a sustained downward trend that would continue into the 1960s; in terms of total production, however, this decline was more than compensated for by the overall increase in population.[133] Per-acre establishment costs were largely unchanged since the 1920s, if not slightly lower, lying somewhere between $150 and $700 depending on the district. The lower bound was noted to be uncommon and likely unsustainable from year to year, while the upper bound was restricted to acreage on the Central Coast. These figures also excluded potential expenditures on wells or housing, which, if necessary, could drive up costs significantly. Production-year expenses were roughly double that of first-year establishment, or $300 to $1100, with picking and transportation amounting to half to two-thirds of the entire expenditure.[134]

Marketing to eastern consumers had become theoretically feasible following the construction of precooling plants during the 1900s and 1910s, and by the 1920s the Central California Berry Growers' Association had managed to send a few shipments as far as New York (albeit meeting with qualified success).[135] Early shipment volume was negligible; the combination of cost, competition, and inconvenience dissuaded most farmers from making the attempt. Chicago was the only city to receive semi-regular shipments, and even then averaged just four carloads per year from 1920 to 1926.[136] During the 1930s, an extended bout of low prices encouraged growers to reappraise these markets. Trade flow remained small but became more consistent, with New York and Chicago receiving anywhere between 20 and 70 carloads annually. Smaller eastern markets, which had never before received Californian shipments, were now sometimes used to offload surplus. Not all districts participated in eastern trade to the same degree, and there were still seasonal limitations; all shipments to markets east of Chicago originated from the Central Coast, and only during the late summer and fall after local production had ended. Outside of the Central Coast, seasons usually concluded before eastern competition subsided, and the volume of late production was typically insufficient to justify cross-country shipments.[137]

Pest pressure continued to reduce economic outcomes and disrupt cultivation systems during the 1930s. Reports from the California Experiment Station indicate that the lifetime

[133] Dennis, *The Location and Cost of Strawberry Production*, p. 2.

[134] Thomas, *The Production of Strawberries in California*, pp. 22–26.

[135] Pacific Rural Press, "Untitled", p. 571.

[136] Strowbridge, *Origin and Distribution*, pp. 26, 71.

[137] Thomas, *The Production of Strawberries in California*, pp. 15–17, 43–61.

of a strawberry planting had decreased from an average of four years to three between 1928 and 1939. Like costs, planting age varied by location, with interior valley districts able to maintain their vines for greater lengths of time than coastal ones.[138] This appears to have resulted in a redistribution of acreage from the Central Coast and towards other districts - although the Central Coast was the most productive region in California, it experienced a marked downturn during the 1930s, falling from 1,330 acres to 1,010 between 1932 and 1938. This change was localized - all other districts expanded their acreage over the same period, with Sacramento in particular bringing an additional 450 acres under cultivation. This implies that district-specific factors - likely the interaction between production costs and pest pressure - were causing growers to exit the region.[139]

On the following page, Figure 4.2 compares acreage, yield, and farm value statistics from 1925 to 1938. In 4.2(a), we see that acreage and yield trends were parallel until the mid-1930s, after which yields began to decline. This was not an unusual phenomenon, and had been observed at different periods and in multiple locations throughout the US. Growers typically ascribed this to strawberry varieties "running out" - a belief that new varieties were initially vigorous, but that over time their health as well as productivity would decline. In actuality, growers were experiencing a combination of accumulated pest pressure, poor cultivation practices, and the spread of viral diseases; we will examine the latter in more detail in the following section.[140,141,142,143] In 4.2(b), we observe a decline in overall revenue from strawberries, otherwise referred to as the farm value of production, did not correspond to a similar decline in acreage, but that it instead remained generally consistent through the 1930s. Figures 4.2(c) and (d) are evidence of the market conditions underlying the growth in eastern shipments.[144] They are also indicative of the cobweb effect in California. We can see that production does not immediately increase or decrease following a dramatic change in prices, but is instead delayed; e.g., 1925/1927, 1927/1930, and 1932/1936. While acreage appears to respond a few seasons after high prices, we do not observe the inverse; the drop in total production between 1933 and 1936 occurred despite acreage remaining relatively unchanged. This suggests growers were maintaining old plantings instead of renewing them, which we would expect given the high initial costs of establishment. This is partial evidence for what we will examine in the following section; specifically, that the costs of investment in establishing a planting and the external capital necessary for the strawberry supply chain to operate effectively were strong deterrents to either relocation or crop rotation.

[138] Hendrickson, *Strawberry Culture in California*, p. 5.

[139] Thomas, *The Production of Strawberries in California*, pp. 8–10, 22–26.

[140] Bain and Hoos, *The California Strawberry Industry*, p. 24.

[141] Zeller, *Crinkle Disease of Strawberry*, pp. 3–4.

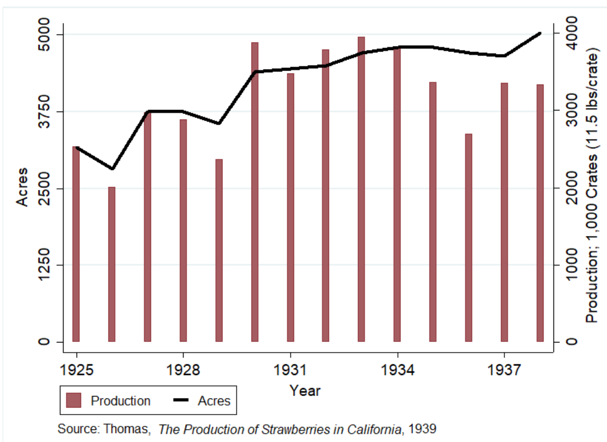
[142] Daniels, *Modern Strawberry Growing*, pp. 1–2.

[143] Thomas, *The Production of Strawberries in California*, pp. 79–80.

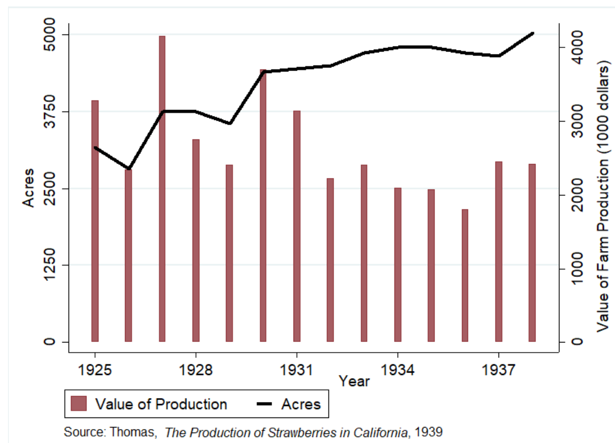
[144] It is not clear whether the California Crop Reporting Service included shipments to markets outside of California when calculating farm value.

Figure 4.2: **California Acreage, Yield, And Value, 1925-1938**

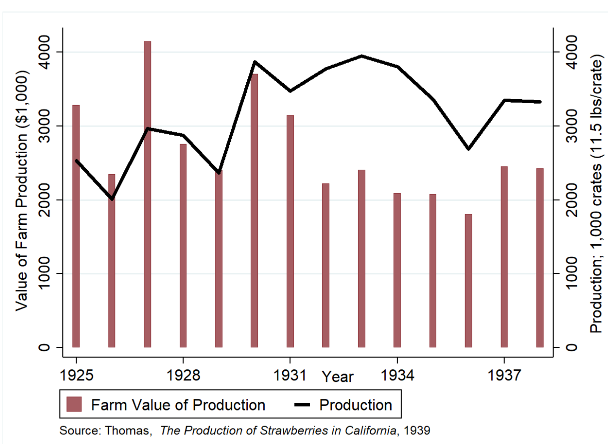
(a) Acreage and State Production



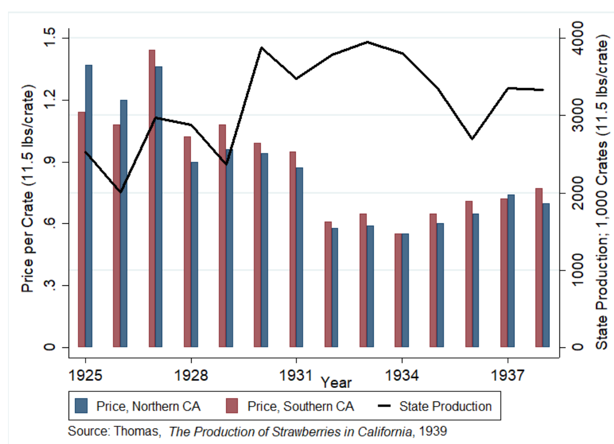
(b) Acreage and Production Value



(c) Production and Farm Value



(d) Production and Prices



Chapter 5

Capital Accumulation and Economies of Density

The increasing sophistication of strawberry production and its associated supply chains had put correspondingly greater emphasis on locational stability in both California and the southern states. In the south, proximity to external capital was paramount to mitigate damage and spoilage prior to shipping. Production density also improved efficiency of external services, such as cooling and shipping. While California producers were less concerned about long-distance shipping, the expense of land preparation and irrigation capital still encouraged repeated cultivation to minimize costs. Both regions, however, dealt with various factors impeding this geographic stability, which had ramifications for the strawberry supply chain as well as growers' economic outcomes.

5.1 The Shipping System

Qualitative evidence indicates that small-scale local production would comprise a non-negligible segment of the industry well into the early 20th century.[1] The shipping system was still poorly equipped to cultivate berries that did not "carry" well even into the 1930s, with two firmer varieties constituting the majority of all carload shipments nationwide. Higher quality berries tended to be softer, restricting them to home markets; according to the Bureau of Agricultural Economics, they were either "grown near the point of consumption or not at all."[2] Together with lower transportation costs, local producers created temporary monopolies in their surrounding area, each one emerging sequentially from south to north as the season progressed.

Over time, however, a more robust supply chain had narrowed the competitive edge of in-season local production over long-distance shipments. Rail companies had made substantial upgrades to capacity and efficiency through the addition of more produce handling and marketing facilities, gauge standardization, and the closing of interregional gaps in the network. Wider application of the telegraph and adoption of the telephone facilitated efficiency gains, providing re-icing stations and strawberry consignees advance notice of incoming ship-

[1] Strowbridge, *Origin and Distribution*, p. 2.

[2] Sherman, *Merchandising Fruits and Vegetables*, p. 452.

ments.[3,4] In 1915, the Department of Agriculture began collecting daily strawberry prices via telegraph, improving growers' responsiveness to distant market conditions.[5] Refrigerated warehouses were becoming increasingly commonplace near points of consumption, reducing product loss and dampening short-term price fluctuations. With sufficient forewarning, producers could also use cold storage at shipping points to wait out brief price depressions.[6] Thanks to their logistical flexibility, motor vehicles were supplanting railroads as the primary method for short-haul shipments by the 1920s; in 1926, roughly one-third of strawberry shipments from Delaware, Maryland, and Virginia were sent by truck.[7] [,8,9] Trucks were also becoming increasingly relevant in California; in 1922, "practically all central California strawberries [were] hauled to market by motor trucks."[10]

5.1.1 Production Density

As discussed in Chapter 3, the strawberry supply chain required a certain level of spatial concentration in order to justify the provision as well as the quality of shipping services and other external capital development. The size of an association, for example, played a major role in the level of influence they were able to exert on railroads during negotiations on freight charges. As the supply chain of strawberry production grew to encompass processing - first canning, then freezing - facilities were also constructed near centers of production. As processors almost always offered lower prices than the fresh market, they depended on berries that would have otherwise gone to waste; according to the *Pacific Rural Press*, "no cannery away from a leading berry district could start to can berries without an assured supply."[11] Proximity to larger districts reduced transportation costs and minimized spoilage prior to processing, while greater volume spread out fixed costs over more units. Associations made their own investments in cooling and cold storage, the magnitude of which was correlated with the resources of their membership. According to Fletcher, two types of precooling equipment were in use in 1917; the first consisted of a refrigerated room connected to a railcar by canvas hood, which cost $1,500 and could chill one or two cars daily. The second involved a system of ammonia-refrigerated coils and large fans that moved cold air throughout the car itself ("cold air blasting"). This reduced cooling time down to four or five hours and eliminated the need to handle the berries more than once, but was also cost-prohibitive; Fletcher did not provide a monetary value, simply stating it was "practicable only for the largest shipping associations and for transportation companies."[12] One such facility was constructed by the Southern Pacific Company at Roseville, California in 1909; a combination ice and cooling plant, it was capable of chilling a car in three hours, though it came with a price tag in excess of $1 million and required a crew of operators on the order of 50 people or more.[13]

[3]Anderson Jr., *Refrigeration in America*, pp. 151–152.

[4]Hedden, *How Great Cities Are Fed*, pp. 74–77.

[5]Sherman, *Merchandising Fruits and Vegetables*, pp. 261–270.

[6]Heagerty, "The American Garden, Vol. 10, No. 7", p. 396.

[7]Approximately 100 miles.

[8]Hedden, *How Great Cities Are Fed*, pp. 6–11.

[9]Strowbridge, *Origin and Distribution*, pp. 26–32.

[10]Pacific Rural Press, "Untitled".

[11]Pacific Rural Press, "Strawberries in North San Joaquin", p. 580.

[12]Fletcher, *Strawberry Growing*, pp. 191–192.

[13]Pacific Rural Press, "Millions for Pre-Cooling in California", pp. 321–323.

Given strawberries' sensitivity to time and physical damage, growers' proximity to capital investments was vital. Bulletins recommended cultivating strawberries within a few miles of a shipping station to minimize the time between picking and refrigeration, as well as any potential damage from hauling.[14] The Missouri Experiment Station also found that berry auction prices were inversely correlated with distance between the grower and the auction itself, and suggested the delay was preventing buyers from adequately inspecting the shipments.[15] Farmers further away from primary localities had reduced access to supporting external capital and found it more difficult to compete in the shipping system. Higher relative transportation costs were unavoidable for individuals or small associations due to their lower volume of production. A farmer cultivating five acres at average yields would require an entire season to produce the equivalent of a single carload of strawberries. To send a single carload daily - a necessity, to ensure they arrived in saleable condition - would require at least 75 to 100 acres near the shipping point; the recommended size of a strawberry production "unit" was roughly 150 to 500 acres within 5 miles.[16,17,18] Individual agents also lacked the marketing infrastructure provided by associations, and were unlikely to be able to afford more than rudimentary cooling facilities on their own.[19] Furthermore, low volume and irregularity in shipments were both correlated with lower-than-average prices when marketing; the Missouri Experiment Station reasoned that buyers tended to rely upon an association's reputation as a quality signal.[20] As a result, strawberry shipments were dominated by just a handful of large districts; the Eastern Shore, the Carolinas, the Ozarks, Tennessee-Kentucky, and Louisiana were responsible for 80 percent of all carloads shipped, or roughly 40 percent of all strawberries sold.[21]

In Figure 5.1, dotted lines indicate the general region over which strawberries fall under the same approximate ripening periods/shipping dates. The first image displays all cultivation for shipping taking place in 1924; here, this is defined as at least ten acres of strawberries within a county. Each of the four largest shipping districts falls under a slightly different shipping period, thus partially avoiding direct competition with one another. The lower image includes *all* acreage - a dot marking any county that recorded any amount of cultivation - which captures both shipping and local markets. Despite the largest centers of production handling the vast majority of shipments, most eastern states still contain numerous small and medium-sized districts for local provision. Notably, every state in the continental US was able to cultivate at least a limited amount of acreage, and highly localized market production persisted even when major shipping centers were nearby. The prevalence of these smaller districts is suggestive of limitations on cooling/shipping capacity outside of large shipping districts; growers without these facilities would need to remain in close proximity to their intended markets.

[14] Wicks, *Strawberry Growing in Arkansas*, pp. 7–8.

[15] Talbert, *Missouri Strawberries*, pp. 70–71.

[16] Strowbridge, *Origin and Distribution*, p. 14.

[17] Talbert, *Strawberry Culture in Missouri*, pp. 11–12.

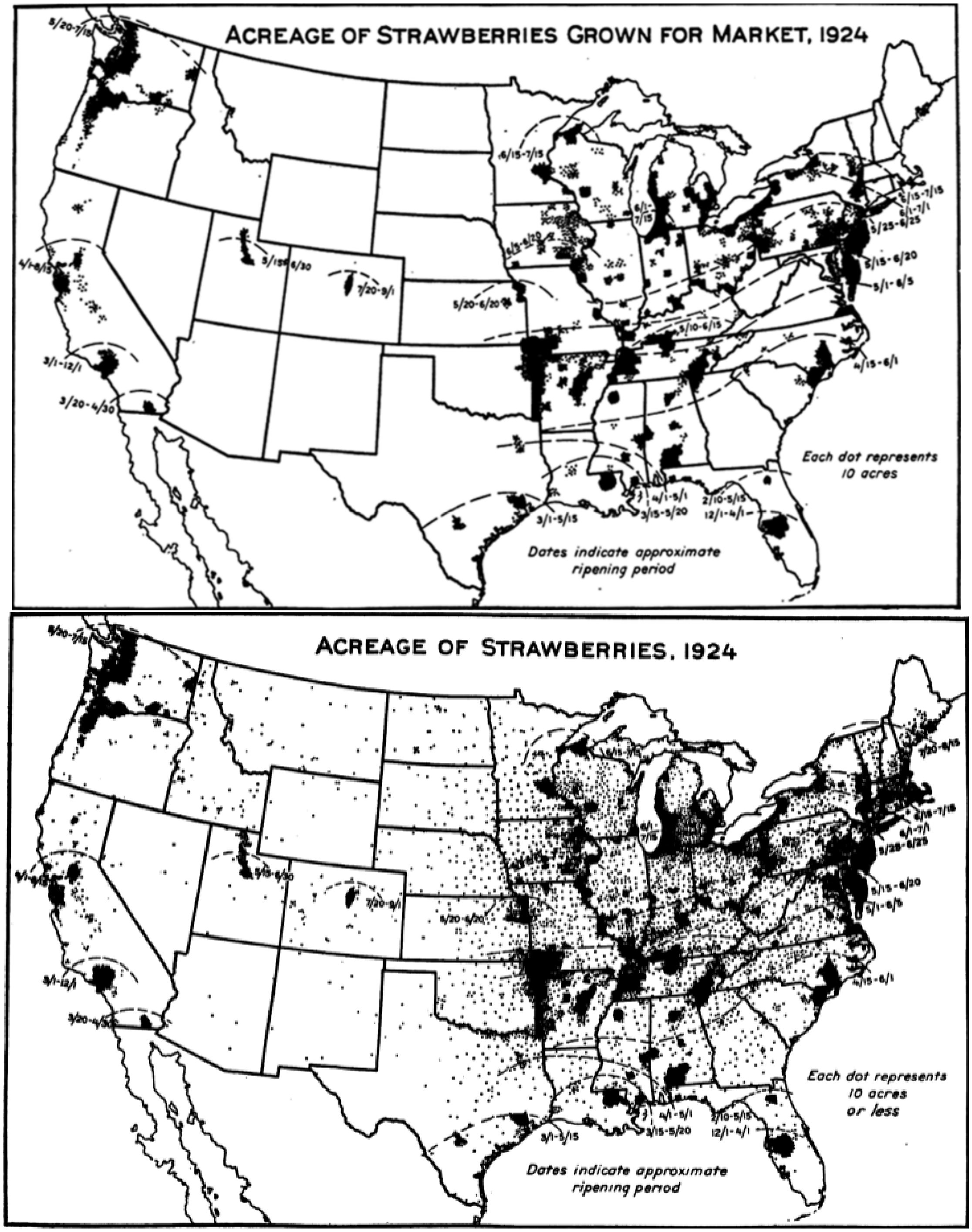
[18] Hutson, *Strawberries and Farm Profits in Western Kentucky*, p. 136.

[19] Wicks, *Strawberry Growing in Arkansas*, p. 44.

[20] Talbert, *Missouri Strawberries*, pp. 68–71.

[21] Strowbridge, *Origin and Distribution*, pp. 13–14.

Figure 5.1: **Commercial Centers vs Total Acreage, 1924.**



Source: Strowbridge, *Origin*, 1930.

5.2 Relocation in the Central South

Unfortunately, proximity to existing capital had been jeopardized by the cultural methods that prevailed in many of the large southern shipping districts. As discussed in a previous section, low prices and cheap land in these districts had disincentivized long-term soil maintenance; the yield effects of fertilization, crop rotation, and even weeding were insufficient to offset their costs. While this inevitably would carry consequences for future agricultural production, investment in strawberry operations was not always recouped; even in the 1930s, the industry was still characterized by "recurrent periods of prosperity for the few and depression for the many."[22] For many growers in the Central South, strawberries were relegated to supplemental crops; too economically unreliable for exclusive cultivation, they were used to absorb surplus farm labor and generate income early in the year.[23] However, this was still vitally important for many low-income farmers. According to the Missouri Experiment Station,

> "In less prosperous parts of [the Ozarks]... strawberries may mean the difference between bare feet and shoes for the boys and girls, while in other cases the payment of delinquent taxes and the interest on the mortgage will depend upon them."[24]

Despite their status as a side crop, there were few alternatives outside of cotton that could generate similar profits to strawberries; from the 1910s onward, the rampant destruction caused by boll-weevil infestations in the south would reduce the opportunity cost of cultivation even further.[25,26]

The primary method growers used to circumvent the loss of soil fertility over time was to relocate their operations to new ground every few years, which was only sustainable as long as there was sufficient land within short distances of shipping facilities. In 1915, one Arkansas Station horticulturist voiced their concern that these methods were "not satisfactory for permanent strawberry production" and that "new land is at the present time quite difficult to obtain."[27] By the 1920s, most of the acreage near these shipping points had been used and discarded, to the detriment of farmers and the strawberry supply chain in general. In 1927, the Station reported:

> "Continued planting on new land has already resulted in some of the growers being ten or twelve miles from their shipping point. At this distance the injury to the berries by being hauled over bad roads, and the time lost to and from the shipping point, are factors which lessen materially the profits of the grower."[28]

[22] F. L. Thomsen and G. B. Thorne, *Economics of Strawberry Production and Marketing In Missouri*, pp. 5–6, 44.
[23] Brannen and Dickey, *Strawberry Production and Marketing in Arkansas*, p. 4.
[24] F. L. Thomsen and G. B. Thorne, *Economics of Strawberry Production and Marketing In Missouri*, p. 5.
[25] Brannen and Dickey, *Strawberry Production and Marketing in Arkansas*, p. 4.
[26] Efferson, *Farm Management and Cost Study*, pp. 6–9.
[27] Wicks, *Strawberry Growing in Arkansas*, p. 7.
[28] Brannen and Dickey, *Strawberry Production and Marketing in Arkansas*, p. 7.

Observations from the Missouri Station indicate similar issues were developing; by 1930, "new land [had become] scarce in many sections and, in some instances, practically impossible to obtain near shipping centers."[29]

This land use practice was well-documented in Arkansas and Missouri, and appears to have extended throughout much of the South. In general, lower costs of land made it more profitable for plantations to be cultivated for multiple years, but the longer a bed was kept, the greater the injury from weeds, pests, and diseases. Renewing an old field also became more expensive as these elements accumulated. In the Ozarks, strawberries were fruited from five to seven years, and in Kentucky, Tennessee, and the northern districts of the Gulf States up to three; outside of this region, strawberries were more commonly annual or biennial crops.[30] This method of cultivation was presumably linked to the nematode infestations that had become endemic to many of the major Southern strawberry districts by the 1920s. Damage caused by nematodes, known as "root-knot," was severe enough in some areas that the local industry had been abandoned; this had reportedly occurred in "what was formerly one of the largest shipping points in the South."[31] A USDA bulletin by George Darrow suggests that the only control method available was starving the infestation, either by fallowing the field or rotating to nematode-resistant crops for two to three years. Unfortunately, many valuable crops, including cotton, cabbage, and fruit trees, were also nematode-susceptible hosts, limiting the options for rotation. If this was financially infeasible, the remaining alternative was to cultivate new land ostensibly free from infestation. However, the long-term sustainability of this practice was questionable; Darrow noted that previously-uncultivated land had become progressively more difficult to find in the South, implying growers outside of Arkansas and Missouri were experiencing similar disruptions to their supply chain.[32]

5.3 Relocation in California

Though strawberry culture in California was far more intensive - and expensive - than the Central South, growers had adopted similar migratory practices. The extended lifespan of plantings, a reaction to high costs of establishment, also served to increase pest pressure by providing them a stable habitat and source of nutrients. In addition, second plantings were extremely rare, as repeated cultivation was known to have a deleterious effect on future production; documents indicate growers in the Pajaro Valley had identified a malady known as "strawberry sickness" no later than 1914. Given the cost of irrigation, it is unsurprising that growers "complain[ed] about even the possibility of such deterioration."[33,34] Later, these issues - along with a host of other biotic and abiotic factors - would fall under a broad affliction known as the "replant problem."

[29] Talbert, *Missouri Strawberries*, p. 4.

[30] Fletcher, *Strawberry Growing*, pp. 237–242.

[31] Darrow, *Strawberry Culture: South Atlantic and Gulf Coast Regions*, p. 8.

[32] Ibid., pp. 7–9.

[33] Lipman, *The Management of Strawberry Soils in the Pajaro Valley and Its Problems*, pp. 3–4.

[34] W. Mackie, *Soil Survey of the Pajaro Valley*, pp. 12–19.

5.3.1 Intercropping

As most growers in California found it cheaper to relocate than attempt to remediate old land, it became necessary to balance periodic relocation with the irrigation capital required for strawberry production, especially as profits fell and costs of labor rose.[35] This was achieved through intercropping - planting strawberries between other crops that took longer to reach maturity, providing the landowner an immediate source of income to offset much of the expense of establishment. This economy of scope between perennial crops and shorter-lived ones is a common arrangement in contemporary sustainable agriculture (see, for example, Malezieux et al., 2009)[36]. Orchards and vineyards were the most common "permanent" crops used for strawberry intercropping; they reached bearing age over the course of four to five years, roughly the duration of a single strawberry planting. While the landowner might choose to cultivate strawberries themselves, this was typically left to tenants. Orchard leases, cash rentals, and crop-share arrangements were all employed to varying degrees.[37]

Intercropping provided a mutually beneficial arrangement for both strawberries and permanent crops. Thousands of acres of orchards were facilitated by strawberry production, particularly in the apple industry; by 1910, sixty percent of the apple orchards in the Pajaro Valley - 9,000 acres - had been established using strawberries as intercrops.[38,39] For strawberry growers, intercropping provided access to fertile soil typically occupied by more valuable fruit trees, and leases on previously uncultivated land also mitigated the risk of pest pressure.[40] In later contracts, water availability was also guaranteed; if the landlord failed to provide the agreed-upon amount, they were liable for any costs incurred by the tenant in acquiring it, up to $1,000.[41] Capital investment was higher under this arrangement; concrete irrigation piping, for example, was more efficient and required less labor to operate, but was too expensive to install for strawberry crops alone.[42] This effect on capital investment may have also held true in reverse, as well. Despite the sizeable yield increases attributed to irrigation, a Santa Cruz soil survey reported that orchards had only recently begun to irrigate by the mid 1940s; however, they also noted that in previous years, strawberry cultivation had required orchardists to set up irrigation systems.[43]

Strawberries came to be defined by their status as a precursor to other, more permanent crops.[44] This did not, however, resolve the underlying issue of fertility loss. In some cases, the leasing system may have even exacerbated it; short-term tenants, like those in the Gardena district of Los Angeles, were indifferent stewards of their soil fertility.[45] In addition, orchards were semi-permanent and thus not conducive to rotation. Over time, their extension gradually displaced strawberries into regions less suitable for cultivation,

[35] United States Senate Immigration Commission, *Immigrants in Industries*, pp. 387–388, 403–404.
[36] Malézieux et al., "Mixing Plant Species in Cropping Systems: Concepts, Tools and Models. A Review".
[37] Adams, *California Farm Tenancy and Methods of Leasing*, pp. 88–89.
[38] W. Mackie, *Soil Survey of the Pajaro Valley*, pp. 12–19.
[39] Darrow, *Strawberry Culture: Western United States*, pp. 18–19.
[40] W. Mackie, *Soil Survey of the Pajaro Valley*, p. 16.
[41] Adams, *California Farm Tenancy and Methods of Leasing*, pp. 88–89.
[42] Hendrickson, *Strawberry Culture in California*, pp. 5–6.
[43] Storie et al., *Soil Survey of the Santa Cruz Area, California*, pp. 12–13.
[44] Hendrickson, *Strawberry Culture in California*, p. 5.
[45] Nelson et al., *Soil Survey of the Los Angeles Area*, pp. 14–15.

causing intensive strawberry districts to be "somewhat migratory."[46] This displacement can be observed through successive soil analyses of the Santa Cruz region. Strawberries were reportedly introduced to the area in approximately 1880, and were originally grown on alluvial soils - fertile land where silt and clay were deposited by running water, and ideal for orchard production. By 1910, the largest concentration of strawberries was situated on clay loam adobe soil; heavier and harder to cultivate, but also the only alluvial soil in the valley that had not yet been cropped to orchards.[47] By the 1930s, strawberry cultivation had been relocated to loam soils outside of the valley, which required greater amounts of fertilizer and could complicate irrigation depending on the composition of the subsoil. Compared to earlier alluvial soil, peak yields on these soils were reduced by an estimated 10 to 30 percent.[48,49]

5.3.2 Strawberry Disease

Pest predation and disease in the California strawberry industry were initially of minimal concern. Strawberries were "quite hardy, and very little subject to diseases of any kind,"[50] and California fruit production in general "[was] almost entirely exempt from disease or insects."[51] This was, of course, temporary, as pest pressure would intensify over subsequent decades. By the 1920s, strawberries were now "subject to attacks by many diseases and insect pests, some of which are difficult to control."[52] As the severity of damage and costs of control escalated, cultivation manuals placed greater emphasis on pest management. Early chemical control methods for strawberry pests were generally applied as sprays; these included various oil emulsions for insects and the Bordeaux mixture, a widely-used fungicide comprised of copper sulfate and lime. Other pesticides were available, including sulfur, nicotine dust, and lead arsenate, but these were used more sparingly: sulfur had the potential to damage the leaves of the plants, while nicotine and lead arsenate left residue on ripening berries.[53] Table 5.1 provides a short description of some of the most common pests and diseases of California strawberries in the early 20th century, as well as any available methods of control.

Preventative cultural practices were required for particularly serious pests and diseases. Farmers were advised against setting new plants on ground known to be infested, and to immediately destroy and remove plants suspected of harboring pests or diseases; this practice was often referred to as "roguing." Long-term maintenance of plantings was discouraged, and extension bulletins recommended that growers should remove and replant to a different location on a regular basis. Farmers could additionally inhibit pest growth by altering planting timing, which disrupted habitats and food supply. They could also reduce the risk of cross-contamination between fields by ensuring adequate drainage (for fungal pests), physical separation (for insects), and that old plants were destroyed well before new ones were set. Yield losses could be mitigated by adopting cultivars with pest or disease resistance.

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[46] Hendrickson, *Strawberry Culture in California*, p. 20.
[47] W. Mackie, *Soil Survey of the Pajaro Valley*, pp. 18–19.
[48] Storie et al., *Soil Survey of the Santa Cruz Area, California*, p. 14.
[49] Storie, *Natural Land Divisions of Santa Cruz County*, p. 47.
[50] Gillet, *Fragariculture*, p. 25.
[51] Hooper, "California Horticulturist, Vol. 1", p. 330.
[52] Hendrickson, *Strawberry Culture in California*, p. 16.
[53] Ibid., pp. 16–18.

Table 5.1: **Common Strawberry Ailments; California, Early 1900s**

Pest/Disease	Characteristics	
	Description	Control
Leaf Spot	Fungal disease of strawberry foliage that causes small dead patches on leaves. Common in occurrence but rarely severe.	Central Coast growers were known to remove leaves prior to spring growth; this likely prevented any significant damage. Fungicide could be sprayed if necessary.
Red Spider/ Two Spotted Mite	Small, plant-feeding mite; signs of infestation include webs and silver spots on leaves. Serious in spring and early summer, and infestations stunt plant growth completely.	Oil emulsion spray on underside of all plants; heavier infestations required multiple sprays. Sulfur effective but could cause foliage burn in warm weather.
Powdery Mildew	Fungus that injures fruit and foliage; causes leaves to curl inward, turn red. Cases were primarily in coastal districts during damp weather and could result in considerable injury.	No satisfactory method of control by late 1930s; peak mildew period coincided with warm weather, making sulfur applications risky.
Strawberry Aphid	Leaf-feeding insect that propagates in fall/early winter and feeds on the plant the following spring. The most damaging aspect, however, were the diseases it transmitted between plants.	Oil emulsion or nicotine sulfate solution recommended for aphid control. However, disease prevention required significant cultural adaptation, discussed in Section 5.3.3.
Cyclamen Mite	Mite that feeds on flowers and leaves; extremely small, almost invisible to naked eye. Overwinters in plant crown and causes tremendous damage the following year; leaves are stunted, plants unable to bear fruit. Responsible for failed plantings in multiple districts.	Because it lives in the crown of the plant, it is unaffected by most pesticides. Propagating stock, however, can be treated by hot water immersion. Varieties descended from the Marshall strawberry were thought to possess some resistance.

Sources: Hendrickson, *Strawberry Culture in California*, 1928; Thomas, *The Production of Strawberries in California*, 1939.

However, this method was more effective when sources of pest pressure were few in number, as resistance traits were usually pathogen or pest-specific and provided only incomplete protection. Selecting disease-free nursery stock was critical but also challenging, as disease symptoms were not always expressed by the plant or recognized by the nursery. For certain pests, growers adopted specific cultural methods: control of the cyclamen mite, for example, involved immersing planting stock in hot water for a half-hour prior to setting the plants. This was highly effective, but required careful monitoring of temperatures to prevent fatal injury to the plant.[54]

5.3.3 Xanthosis

One of the most widespread and destructive diseases of the strawberry was the viral disease "yellows," later known as xanthosis. Observed for the first time in 1915 on the Central Coast, xanthosis was the first recognized viral disease of strawberries and would eventually affect almost all strawberry districts within the state, disrupting the strawberry supply chain and forcing the industry to alter cultural practices. The disease is primarily transmitted through the feeding habits of strawberry aphids, which are able to carry the virus between hosts. Their mobility threatens all other plantings within a few miles of an infected field, further complicating efforts to contain the disease; the virus is also passed down from mother to daughter plant, making xanthosis infection effectively permanent. This is also why it poses a particular threat to nursery production, as it renders affected propagation stock worthless. The Marshall cultivar, the leading strawberry when xanthosis first emerged, was not only highly sensitive to the virus, but also had a large proportion of its planting stock contaminated.[55,56]

Characteristic symptoms of xanthosis include the curling and discoloration of new leaves, stunted growth, and root decay; affected plants are permanently weakened and produce smaller yields. Infection is not typically fatal, but it often occurs in conjunction with other viral diseases.[57] There are no readily available statistics for the economic damage caused by xanthosis, but it was known to be unevenly distributed. The disease was particularly virulent in the Central Coast districts, where infection would reduce potential yields by half; in contrast, outbreaks in the central valley districts were rarely if ever severe. Besides directly reducing yields, xanthosis also indirectly curtailed the lifetime of plantings. Older stands of strawberries were more likely to become infected, as well as endanger other nearby acreage in the process; on the Central Coast, the average planting length was reduced by at least a year in response. Roguing infected plants to prevent transmission was made more challenging by the varying degrees of symptomatic expression, as carriers often appeared healthy until the disease progressed and manifested symptoms.[58] Warm summers, common to propagating districts, also temporarily reduced symptom expression.[59]

[54]Thomas, *The Production of Strawberries in California*, pp. 73–80.

[55]Darrow, *The Strawberry*, pp. 230–231.

[56]Converse, Martin, and Spiegel, "Strawberry Mild Yellow-Edge", pp. 25–26.

[57]Ibid., p. 25.

[58]Plakidas, "Strawberry Xanthosis", pp. 1058–1062, 1088.

[59]Thomas, *The Production of Strawberries in California*, pp. 79–80.

Without a cure, growers adopted multiple preventative measures to check the spread of disease and the damage it caused. One locally successful effort was the introduction of a xanthosis-resistant cultivar from Ohio known as Nich Ohmer, which was grown around Watsonville and Salinas in the 1920s and 1930s.[60,61] Its cultivation was limited in scope due to its sensitivity; compared to the Marshall, it was "exacting in [its] requirements," performing poorly on heavier soils and those with elevated salt and alkali content. Despite its resistance to xanthosis, it was susceptible to a host of other diseases.[62] Elsewhere, partial mitigation of the disease was achieved by adapting production practices to aphids' life cycles and behavior. Spring planting became more common; as aphid populations were highest early in the year, plants set after mid-April were less likely to be affected in their first year, when they were most vulnerable. Physical distance between plantings - two to three miles - also reduced the likelihood of inter-field migration. If these preventative measures failed, a farmer would typically abandon the field altogether.[63]

5.3.4 Brown Blight/Verticillium Wilt

In addition to xanthosis, growers were forced to deal with sporadic outbreaks of "brown blight," a soil-borne disease that received its name for the discoloration and defoliation it caused in affected plants. It is not entirely clear when this disease began to affect in California agriculture. Guthman, for example, suggests brown blight had appeared in strawberry production by 1920 - likely referring to a major outbreak that devastated the Driscoll-Reiter farm that year - while Wilhelm and Sagen claim it was first recognized in 1912, citing a newspaper article in which an Elk Grove nursery mentions difficulty in preventing blight-related damage. There is even tentative evidence that outbreaks may have appeared much earlier; in 1880, the *Pacific Rural Press* reported one Stanislaus grower was losing plants to a "strawberry blight" of unknown origin, which had caused severe foliar desiccation and atrophy.[64,65,66,67] The reliability of these earliest sources is somewhat confounded by ignorance of blight's causative agent and the similarity of symptom expression between different pathogens. Nomenclature also presents a challenge, as "blight" could be used as a placeholder for a malady of unknown origin, or for an unrelated disease with overlapping symptoms: e.g., "leaf blight," an unrelated disease which also results in foliar damage.

By the late 1920s, the Experiment Station tentatively concluded that blight was a fungal infection - a "root rot"[68] - though the specific cause remained undetermined until 1931. Reports of blight in strawberries were relatively uncommon, but early accounts suggest they could result in catastrophic losses. Its severity was thought to be influenced by cultivar choice - the disease "affect[ed] some varieties to such an extent that the whole field is destroyed."[69]

[60] S. Wilhelm and James Sagen, *A History of the Strawberry*, p. 216.
[61] Darrow, *The Strawberry*, p. 153.
[62] Thomas, *The Production of Strawberries in California*, pp. 25, 64–66.
[63] Ibid., pp. 56–57, 79–80.
[64] Guthman, *Wilted*, p. 28.
[65] S. Wilhelm and James Sagen, *A History of the Strawberry*, pp. 191–213.
[66] Not Listed, "Strawberry Blight".
[67] Tribble Bros., "California's Strawberry Culture", p. 653.
[68] Hendrickson, *Strawberry Culture in California*, p. 17.
[69] Tribble Bros., "California's Strawberry Culture", p. 653.

Mitigation was additionally hampered by growers' incomplete understanding; one Station bulletin, for example, recommended aggressive roguing under the impression that the disease only occurred in the spring.[70] Post-1920s, however, the severity and frequency of brown blight outbreaks would intensify, progressing to the point where it became one of the primary limiting factors of strawberry production.

In 1932, Harold Thomas of the California Experiment Station would identify the causative agent of blight as the soil-borne fungus *Verticillium dahliae*.[71] *V. dahliae* encompasses multiple strains of the most widespread and broadly pathogenic species of the genus *Verticillium*. *V. dahliae* pathogenize plants through abrasions on the roots, after which it propagates inside the xylem and eventually kills the host through water deprivation. The fungus is immobile in the soil, but can be spread to new areas through several means, including inoculated plant matter, contaminated irrigation water, or improperly cleaned equipment. Infections are also capable of moving between root systems that are in contact with one another. *V. dahliae* possesses a multiplicity of strains which differ in their virulence to specific crops, but wilt damage is typically extremely severe. In strawberries, most commercial cultivars possessed - and continue to possess - extreme susceptibility to even minor infestations. Depending on the level of soil inoculum, losses could reach upwards of 75%.[72] The damage caused by *V. dahliae* is further compounded by how difficult it is to control or destroy. Crop rotation is of little benefit; it is able to colonize hundreds of different, often economically-valuable crops, and can survive even in hosts that it does not have a pathogenic relationship with. When no host plant is available, it forms resting structures in the soil known as microsclerotia, which become active again once a host is introduced. These microsclerotia are resistant to high temperatures and dehydration, and can remain viable in the soil for an extended period of time. Certain crops, as well as a variety of asymptomatic weeds, can also introduce *V. dahliae* into previously uncontaminated fields.[73]

V. dahliae currently affects agricultural production in almost all temperate regions worldwide, though it remains unclear as to why fungal infestation is so widespread and why it appears to have become increasingly more virulent from the late 19$^{\text{th}}$ century onward.[74,75] Some of this can be attributed to the adoption of irrigation and nitrogen fertilizers; experiments have demonstrated that imbalanced nitrogen is associated with greater disease severity, and that excessive soil moisture aids in microsclerotia germination and colonization. Continuous cropping also increases fungal density in the soil, even when the host plant is ostensibly asymptomatic. Even dead plant material acts as a pathogen reservoir, releasing microsclerotia into the soil as it decomposes.[76,77] The Nich Ohmer was discovered to be extremely susceptible, and the incidence and severity of outbreaks rose in locations where it had supplanted the Marshall; this may have exacerbated local *V. dahliae* density.[78] By the

[70] Hendrickson, *Strawberry Culture in California*, p. 17.

[71] In earlier literature, there was some taxonomic confusion regarding *V. dahliae* and another related species, *V. albo-atrum*. It is now accepted that the two pathogens are distinct.

[72] Thomas, *Verticillium Wilt of Strawberries*.

[73] S. Wilhelm and Ferguson, "Soil Fumigation Against Verticillium Albo-Atrum".

[74] Pegg and Brady, *Verticillium Wilts*, pp. 176–179.

[75] Rudolph, "Verticillium Hadromycosis", p. 202.

[76] Bell, "Verticillium Wilt", pp. 87–89.

[77] Wheeler et al., "Effects", pp. 985–988.

[78] S. Wilhelm and James Sagen, *A History of the Strawberry*, pp. 216–220.

end of the 1930s, *V. dahliae* had become a limiting factor in many areas, and was poised to be the most serious threat to strawberry cultivation in the state.[79]

Thomas's 1932 report noted that some varieties of strawberry exhibited resistance to Verticillium wilt, and could potentially provide a genetic foundation for future commercial cultivars.[80] The relative value for these resistance traits was particularly high; unlike xanthosis, there were few methods available to growers for preventing or mitigating damage from wilt, and new plantings were effectively forced into gambling on whether or not *V. dahliae* was present in the soil. Over the next twenty years, however, selective breeding efforts for wilt resistance appear to have been uncommon or possibly ineffective.[81] Regardless, any attempts would have inevitably dealt with two major complicating factors: first, that the progeny of wilt-resistant varieties were often found to be susceptible, and second, that many varieties that exhibit wilt resistance also possess characteristics that reduce their performance commercially. By the 1960s, the University of California's strawberry breeding program was investigating a potential genetic correlation between high levels of resistance and undesirable commercial traits, a connection which has since been supported by later research.[82,83] This was arguably observable in the Marshall and Sierra cultivars, both of which expressed a degree of Verticillium tolerance; the Marshall was highly susceptible to xanthosis, and the Sierra, at roughly half the yield of the Lassen, was comparatively unproductive.

However, even if a hypothetical cultivar was both resistant and commercially viable, it is still unclear how long-term such a solution would be. Wilt resistance in other verticillium-affected crops such as cotton or tomatoes is a single component of management; resistant cultivars are adopted alongside a host of other cultural practices, including rotation with grasses, improving soil drainage, and removing crop residue. Other practices are adopted, not to reduce *V. dahliae* density, but to improve plant health in order for it to survive fungal colonization. Resistance is also subject to the dynamics of evolutionary pressure on pest populations. Based on experiments with cotton in the 1950s, planting resistant varieties selected for increasingly virulent strains of Verticillium, which then comprised an increasing proportion of the soil inoculum. These cotton cultivars were rendered ineffective within a decade from their introduction, suggesting that resistant cultivars are useful only until the local population adapts to the defenses of its hosts. Though these results are not directly comparable, it is not beyond the scope of imagination that strawberry resistance would be subject to similar limitations.[84] Furthermore, California soil was known to host to at least two *V. dahliae* strains pathogenic to strawberries, meaning resistance to one form was no guarantee of protection from another.

Wilt mitigation was uncommonly difficult. The presence of the disease was difficult to detect before symptoms became severe, and was often mistaken for poor irrigation until the weather grew warmer. As wilt was soil-borne and spread through strawberry roots, roguing and replanting had no effect on disease pressure; the removal of first-year blossoms appears

[79]Thomas, *The Production of Strawberries in California*, p. 80.

[80]Thomas, *Verticillium Wilt of Strawberries*, pp. 9–15.

[81]Sherbakoff, "Breeding for Resistance to Fusarium and Verticillium Wilts", p. 406.

[82]Darrow, *The Strawberry*, p. 229.

[83]Bolda and Koike, *Verticillium Wilt in Strawberries: California 2013 Update.*

[84]Bell, "Verticillium Wilt", pp. 90–107.

to have regained popularity to ensure plants were well-established before bearing, mitigating the effects of fungal colonization.[85,86,87,88] Early extension bulletins recommended three and four year rotations between each strawberry planting, which met with some success outside of California; verticillium outbreaks were typically less severe in other climates and soil compositions, and local varietal resistance may have also played a role.[89] Unfortunately, many of the crops that would be otherwise desirable to rotate with strawberries were themselves susceptible to wilt. Furthermore, short rotations in general were unable to control Verticillium in key California districts, as the favorable soil composition allowed microsclerotia to persist for a decade or more even in the absence of a host.[90,91] Farmers could still choose to reduce soil inoculum with non-susceptible rotations, although those that did were restricted to less profitable crops such as grain or beans; even then, microsclerotia could still persist in the soil for a decade.[92]

The most common method of dealing with wilt was simply avoidance. However, a field's status was typically unknown prior to planting; growers came to depend heavily on crop histories as a result, rejecting any acreage previously used to grow wilt-susceptible crops. In particular, growers avoided any land where crops in the solanaceous family - including tomatoes, eggplants, peppers, and potatoes - had been planted, all of which had been linked to previous outbreaks. As disease severity worsened, the recommended number of seasons between strawberries grew longer, as did the list of previous crops growers were supposed to avoid. The combination of the replant problem and avoidance of verticillium wilt created a nomadic strawberry culture: farmers relocated every few years and generally would not return to older acreage.[93] Along with the overlap between strawberry and solanaceous growing regions, this would cause existing agricultural districts to become less and less suitable for strawberry production. As crop histories became longer and less reliable, farmers sought out acreage in districts that had been less extensively cultivated; new soil was preferable, but they would also cultivate old pasture land or recently-removed orchards.[94] This pattern of migration persisted until the late 1950s, when the advent of soil fumigation in strawberries - first with chloropicrin, then with chloropicrin/methyl bromide mixtures - provided growers a method of controlling verticillium wilt.[95,96]

[85] S. Wilhelm and Ferguson, "Soil Fumigation Against Verticillium Albo-Atrum".
[86] Hendrickson, *Strawberry Culture in California*, p. 11.
[87] Thomas, *The Production of Strawberries in California*, p. 38.
[88] S. Wilhelm and Paulus, "How Soil Fumigation Benefits the California Strawberry Industry", p. 267.
[89] Thomas, *Verticillium Wilt of Strawberries.*
[90] S. Wilhelm and Ferguson, "Soil Fumigation Against Verticillium Albo-Atrum".
[91] Curl, "Control of Plant Diseases by Crop Rotation".
[92] S. Wilhelm, *Diseases of Strawberry: Guide for the Commercial Grower*, pp. 6–7.
[93] Thomas, *The Production of Strawberries in California*, pp. 48–50.
[94] S. Wilhelm and Paulus, "How Soil Fumigation Benefits the California Strawberry Industry".
[95] Dean and C. M. Jr., *Trends for Major California Crops.*
[96] S. Wilhelm and Paulus, "How Soil Fumigation Benefits the California Strawberry Industry".

Chapter 6

Fumigation

Fumigation has been used as a means to control pests for millennia, but has only existed as a formal scientific discipline for a small fraction of that time. As fumigants occupy a dual role as both poison and a critical component of agricultural production, there is an ongoing balancing act taking place between requirements of efficacy, safety, and economy, all of which occurs under imperfect information. To understand the importance of methyl bromide, it should be discussed in the context of how fumigation as a practice has evolved over time.

6.1 Background

6.1.1 Types of Fumigation

Agricultural fumigation can be separated into two very broad treatment categories. The first, “space” fumigation, involves volatilizing a chemical inside some form of container; early treatments were typically applied inside buildings or under makeshift tents, but has since extended to fumigation of sealed chambers, storage facilities, and greenhouses. A specific dosage of the fumigant is allowed to permeate the container for a predetermined period, based on a chemical- and pest-specific set of criteria that adheres to some form of the function $Lethality = Dosage * Time$. Space fumigation is often used to prevent agricultural shipments from spreading pests between regions - this is specifically referred to as quarantine treatment. The second category is soil fumigation, which is typically performed by pressurizing the chemical into a liquid, injecting it into the ground, and allowing it to volatilize and disperse in the soil.[1] Early soil fumigation was often performed while the crop was already in the ground and was in many cases a sort of chemotherapy - achieving the right dosage to kill the pest without killing the plant. Farmers would attempt to limit off-gassing by tamping down the injection site by foot and wetting the soil; occasionally, coated paper was also used to cover the field. Modern soil fumigation is now virtually always a pre-plant operation; applied chemicals are expected to have dissipated from the soil before crops are set (though this is not always the case). With the advent of plastic, farmers also began to cover fields with sheets of polyethylene. In specific cases, soil fumigation can also be categorized as quarantine treatment, such as the movement of nursery plants from one region to another.

[1] Bourcart, *Insecticides, Fungicides, and Weed Killers.*

Of the two categories, soil fumigation faces arguably the largest challenges, as treatment occurs in an uncontrolled environment where not all of the biological components and their interrelationships are fully understood. A field can host numerous economically-relevant pests from different biological kingdoms, and may necessitate the usage of multiple fumigants to manage them simultaneously; this increases the risk that applications will have unintended consequences for non-target biota. What was thought to be a lethal application may not persist long enough in the soil or may not fully disperse throughout the field, leading to uneven or sub-optimal pest control. Compared to space fumigation, soil fumigation also carries additional risk to human and environmental health, encompassing issues like accidental leakage, pesticide drift, and groundwater contamination. Modern space fumigation is generally not subject to the same idiosyncrasies, as many of the parameters - fumigant concentration, length of exposure, chamber temperature - are directly under the applicator's control. However, a key difference is that the treated plant or produce is directly exposed to the fumigant, which shortens the list of viable chemicals; many fumigants that are lethal to pests will also cause undesirable damage to their hosts, affecting their condition, taste, or leaving behind chemical residue. Today, only two chemicals, phosphine and methyl bromide, are approved for quarantine fumigation of consumable agricultural goods.

6.2 19$^{\text{th}}$ Century Fumigants

Chemical pest control - and by extension, fumigation - had become a burgeoning scientific discipline by the mid to late 19$^{\text{th}}$ century. New potential compounds and application methods were tested under controlled settings, often by or at the behest of government agencies, and experimental designs and results were made available in agricultural bulletins or academic publications. However, these developments also preceded any regulatory framework governing commercial production or application. Early fumigant manufacturing was not standardized, and products sold to growers were typically labeled with approximations of their purity; often, they were fraudulently mislabeled or adulterated. In 1905, the Georgia State Board of Entomology reported that the majority of cyanide compounds sold to nurseries for fumigation were impure, in some cases to the point where they were unfit for use.[2] The accidental poisoning of farm workers was not unusual in the course of fumigating. There were also serious omissions in consumers' regulatory protections; tolerances for pesticide residue, for instance, went completely unregulated until the mid-1930s.[3,4] Below, we discuss the two most prominent fumigants of this period, discussing their usage as well as their general deficiencies.

6.2.1 Carbon Disulfide

Carbon disulfide (CS_2), the first fumigant ever issued a patent in the United States, was also the first to have been adapted for soil fumigation.[5] In 1869, Baron Paul Thenard of France

[2]Newell, *An Inquiry into the Cyanide Method of Fumigating Nursery Stock*, pp. 369–370.

[3]Graham, "Federal Regulation of Pesticide Residues", pp. 99–103.

[4]Legge, "Occupational Hazards in the Agricultural Industries", pp. 461–462.

[5]Ren and S. Allen, "A Reappraisal of an Old Fumigant, Carbon Disulphide, Under Modern Farm Storage Conditions", p. 516.

performed perhaps the first experimental treatment of soil in an attempt to control grape phylloxera,[6] an invasive species introduced via agricultural shipments from the United States. The phylloxera was responsible for widespread, catastrophic damage to French viticulture, and within 15 years had affected 2.5 million acres of wine production.[7] Thenard's initial attempts at treatment involved digging out a series of holes in his vineyards and pouring vials of carbon disulfide into them, then filling the holes back in by foot. This rudimentary fumigation was lethal to nearby phylloxera, but had to be made at sufficient distance from the root system or it was also lethal to the plant. However, even if treatment was fatal to the vines, exterminating the phylloxera still left the soil free from infestation and viable for future cultivation; in fact, despite the injury that carbon disulfide caused to living plants, repeated testing demonstrated that fumigated soil provided overall improvements in plant root development and growth response, even to plants that were themselves not damaged by the louse. Plants grown on previously fumigated soil produced larger yields and could be continuously grown on the same land without the need for crop rotation. It was hypothesized that fumigation reduced soil "exhaustion," possibly by increasing the presence of nitrifying bacteria or destroying injurious ones.[8]

The process of fumigating with carbon disulfide would go through a series of much-needed refinements over the next several years. Large-scale experimentation led to new equipment and methods of application to improve efficacy and safety, including hand-held and animal-drawn injectors, as well as a basic framework of proper fumigation procedures.[9] Early treatments had applied immense doses - up to 5,000 pounds per acre - which was cumbersome and imminently fatal to both pest and plant. Later, growers would experiment with dissolving carbon disulfide into water; this emulsion was less lethal and lacked the same penetrative ability in the soil, but it also reduced the likelihood of phytotoxic collateral damage as well as the danger to operators, and improved the uniformity of fumigant distribution.[10] Attempts were made to apply liquid carbon disulfide directly into plowing furrows, but this proved ineffectual despite widespread (though brief) adoption.[11] Over time, direct applications were sufficiently refined so that growers could adopt partial-control treatments that limited the damage to the crop. Applications were reduced to approximately 200 pounds per acre, sufficient to knock down the phylloxera population to more manageable levels without interrupting production. This did, however, delay fruiting as the plant recovered from the treatment, and annual reapplication was necessary in order to maintain control over the remaining insects.[12] These two methods, respectively referred to as "extermination" and "cropping" (or "culture") treatments, were both adopted by farmers, although over time they grew to favor cropping treatments over the more expensive and destructive alternative.[13]

Carbon disulfide would also find use as a space fumigant in the mid to late-19th century. It was first used to control insect infestations of stored grains, proving to be particularly ef-

[6] Grape Phylloxera is sometimes referred to as the grape aphid or grape louse.

[7] S. Wilhelm, "Chemical Treatments and Inoculum Potential of Soil".

[8] Ibid.

[9] Ibid.

[10] Bourcart, *Insecticides, Fungicides, and Weed Killers.*

[11] Newhall, "Disinfestation of Soil by Heat, Flooding, and Fumigation".

[12] Bourcart, *Insecticides, Fungicides, and Weed Killers.*

[13] Hilgard, *The Phylloxera or Grapevine Louse, and the Remedies for its Ravages.*

fective against the black weevil, a species responsible for millions of dollars worth of damage to corn in the southern United States.[14] It was also used to disinfest trees of wood-borer grubs and larvae, although extended exposure or high temperatures could result in unintended damage.[15] Carbon disulfide is still used today for grain fumigation in a limited capacity, particularly in developing countries; elsewhere, it has been largely supplanted by the introduction of phosphine and methyl bromide.[16]

Carbon disulfide would remain the only soil fumigant of any real importance until the early 20th century. However, despite the progress made in fumigation techniques, the chemical itself possessed some inherent and significant drawbacks. The most pressing was its exceptional flammability.[17] The risk of explosion was great enough that farmers were advised to store barrels of carbon disulfide "away from dwellings and protected from the sun."[18] In at least one instance, treated grain inside a storage facility rose to high enough temperatures that it ignited the vapors, resulting in considerable damage to both the grain and the building itself.[19] Other issues with space fumigation included the high level of residues on treated produce and reduced germination rate of seeds. In soil fumigation, the efficacy of treatments was not uniform. While low intensity applications reduced the damage caused by grape phylloxera, they could only do so when infestation was small; greater numbers of phylloxera required more applications, and repeated exposures would impair and eventually kill the vines. Low temperatures greatly reduced carbon disulfide's lethality and its area of control once inside the soil.[20] Even diluted, treatments cost approximately $17.50 to $25 per acre in 1880, or $400 to $550 after adjusting for inflation. Past a certain level of infestation, it became cheaper to replant completely instead of saving the existing vineyard.[21,22] Efficacy also varied substantially between pests; wireworm larvae or root knot nematodes required dosages several times greater than average, and experiments suggested that some species actually responded positively to fumigation.

6.2.2 Hydrogen Cyanide

Space fumigation with hydrogen cyanide (HCN), sometimes referred to as prussic acid or hydrocyanic gas, rose to prominence in the late 1800s. It was first employed in 1886 by D.W. Coquillett after existing sprays had failed to control infestations of cottony cushion scale, invasive pests that feed on trees and were causing extensive damage to Los Angeles orchards. The earliest treatments with hydrogen cyanide involved draping the trees with tents made of heavy, semi-impermeable oiled material, underneath which gas was generated by dripping sulfuric acid onto solid potassium cyanide. A number of technical improvements were developed in the 1890s and early 1900s to improve efficacy as well as safety; tolerances for different insects were experimentally determined, coverings were comprised of new material

[14] Hinds, *Carbon Disulfide as an Insecticide.*

[15] Bourcart, *Insecticides, Fungicides, and Weed Killers.*

[16] Ren and S. Allen, "A Reappraisal of an Old Fumigant, Carbon Disulphide, Under Modern Farm Storage Conditions".

[17] Fleming, *Preventing Japanese Beetle Dispersion by Farm Products and Nursery Stock*, p. 7.

[18] Bourcart, *Insecticides, Fungicides, and Weed Killers*, p. 54.

[19] Hinds, *Carbon Disulfide as an Insecticide*, pp. 532–534.

[20] Newhall, "Disinfestation of Soil by Heat, Flooding, and Fumigation", pp. 206–208.

[21] Hilgard, *The Phylloxera or Grapevine Louse, and the Remedies for its Ravages.*

[22] Noling, "Soil Fumigation".

and designs to reduce weight and facilitate positioning, and new types of generators - first earthen pots, then the hosed "cyanofumer" device - distanced operators from the cyanide vapors and increased the potential scale of treatment. Experiments also demonstrated that the fumigation injuries were correlated with light intensity, temperature, and humidity; growers began to fumigate at night as plant dormancy reduced the likelihood of tissue damage.[23] The initial cost of equipment - tents and fumigator - was somewhat expensive, estimated at roughly $1,500 in 1918. Variable costs, on the other hand, were between $25 and $45 an acre.[24] By 1923, growers in California were spending a total of 2.5 million dollars annually on fumigation.[25] Treatment was also adapted for broader usage, including greenhouses, railway cars, and ships; attempts were also made to apply it as a soil fumigant, but despite the lethality of the treatment it was incapable of diffusing adequately.[26] Over time, other cyanide compounds were introduced; sodium cyanide largely replaced potassium cyanide during World War I due the growing expense of potash, and by the 1920s entomologists were also experimenting with calcium cyanide dust.[27,28,29]

Hydrogen cyanide was an undeniably effective method of controlling orchard pests. However, like carbon disulfide, it was also difficult and often dangerous to implement. The toxin itself acted rapidly on both pest and operator, and the compounds used to generate it readily decomposed when in contact with moisture.[30] Fumigation often caused damage to fruit, particularly if performed after an irrigation, and both production and usage degraded the mechanical components involved. An innovation in tent marking increased the accuracy of dosages, as did new gas generation methods, like the "liquid gas" introduced in 1916. However, this type of fumigation was also associated with operator fatalities and required special containers kept at low temperatures to transport it.[31] To further complicate the fumigation process, none of the three methods - pot, cyanofumer, or liquid gas - was universally more effective under all temperature and weather conditions, and all were negatively affected by low temperatures and moisture.[32]

6.3 20th Century Fumigants

Fumigation practices grew increasingly sophisticated over the 20th century with the introduction of new mechanical applicators, low atmosphere/vacuum fumigation, and numerous synthetic pesticides.[33,34] The federal government would also take its first incremental steps towards a system of pesticide regulation, beginning with the Insecticide Act of 1910. This

[23] Clayton, "Hydrogen Cyanide Fumigation", pp. 489–492.
[24] Woglum, *Fumigation of Citrus Trees*, p. 30.
[25] Woglum, "The History of Hydrocyanic Acid Gas Fumigation", pp. 519–520.
[26] Bourcart, *Insecticides, Fungicides, and Weed Killers*, pp. 131–135.
[27] Woglum, "The History of Hydrocyanic Acid Gas Fumigation", pp. 518–521.
[28] Weigel, *Milestones in Greenhouse Fumigation*.
[29] Quayle, "Fumigation with Calcium Cyanide Dust", pp. 207–211.
[30] Bourcart, *Insecticides, Fungicides, and Weed Killers*, pp. 130–131.
[31] Quayle, "Fumigation with Calcium Cyanide Dust", pp. 209–210.
[32] Woglum, "The California Citrograph, Vol. 6, No. 10", pp. 350–351.
[33] W. Carter, *Fumigation of Soil in Hawaii*, p. 127.
[34] Woglum, "The History of Hydrocyanic Acid Gas Fumigation", p. 521.

was the first national prohibition against adulteration and mislabeling, although it was primarily targeted at ensuring efficacy rather than the safety of their ingredients or application. In 1912, the Plant Quarantine Act created the legal framework for the control of plant diseases and pests via quarantine, which established the Department of Agriculture's authority to regulate trade of certain plants and plant products due to their potential of carrying invasive species or plant diseases.[35] Produce residue tolerances were set by the Food, Drug, and Cosmetics Act (FDCA) in 1938, but enforcement was reactive and required confirmation of a product's toxicity before regulatory action was taken; the Miller Amendment, passed in 1954, extended tolerance requirements to all pesticides. A pesticide registration system was passed in 1947 with the Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA). However, the USDA was criticized by other federal agencies for its persistent failure to enforce compliance, leading to FIFRA falling under the jurisdiction of the Environmental Protection Agency in 1972.[36,37]

6.3.1 Chloropicrin and Other Nematicidal Fumigants

Chloropicrin (trichloronitromethane, CCl_3NO_2), first prepared in 1848, would become one of two major components of mid-20th century strawberry fumigation. It is a heavy, colorless, and noxious gas, exposure to which rapidly induces severe lachrymal responses and vomiting and can be fatal in sufficient quantities. Its future importance was belied by its inauspicious beginnings, as the chemical remained a novelty for the next 60 years until an Austrian company proposed incorporating it as a soap additive, which produced a compound that was both an insecticide and a disinfectant. Its agricultural possibilities were temporarily superseded by its applications in chemical warfare, but the large stockpiles the US accumulated during wartime were soon repurposed.[38] In the 1910s, William Moore's experiments with chloropicrin fumigation identified the chemical as an effective and phenomenally toxic fumigant that could potentially replace carbon disulfide in space fumigation treatments of grain and clothing.[39,40] It was soon discovered to be a potent and generally biocidal soil fumigant, capable of controlling economically-relevant pests across a broad biological spectrum; even as newer pesticides were introduced, chloropicrin served as "a yardstick by which the newer materials have been measured."[41]

Chloropicrin was first used extensively by the Hawaiian pineapple industry, where yields had deteriorated as a result of soil "exhaustion" and nematode damage. Field experiments in 1935 demonstrated yield increases of 30 to 50 percent over non-fumigated land, corresponding to an increase in net revenue of more than $80 per acre. Fumigation with chloropicrin quickly became standard practice on pineapple farms, encouraged by artificially low prices; military stockpiles, which had built up in Hawaii during wartime, had been declared surplus and sold

[35] Devorshak, "History of Plant Quarantine and the Use of Risk Analysis", pp. 20–22.
[36] Graham, "Federal Regulation of Pesticide Residues", pp. 99–103.
[37] Committee on Agriculture, "Data and Trade Secret Issues", pp. 156–158.
[38] Roark, *A Bibliography of Chloropicrin, 1848-1932*, pp. 1–2, 35.
[39] Moore, "Volatility of Organic Compounds as an Index of the Toxicity of Their Vapors to Insects".
[40] Moore, "Fumigation with Chloropicrin".
[41] Newhall, "Disinfestation of Soil by Heat, Flooding, and Fumigation", p. 214.

at significant discount to pineapple growers.[42,43] Compared to carbon disulfide, chloropicrin was effective across a wider variety of pests, required lower dosages for control, and was non-flammable; it also acted as a promoter of root development and general soil vigor, generating a positive yield response in crops planted to fumigated soil through some unknown mechanism.[44,45] However, while chloropicrin was safer to handle than carbon disulfide, it was generally unpleasant to apply due to its noxious vapors, and it also possessed a tendency to corrode fumigation equipment. Soil and moisture conditions were also a concern, as chloropicrin was prone to adsorption in clay soils and did not diffuse as readily as carbon disulfide; one report noted that it "was 14 times as toxic as carbon disulfide in the air, [but] was only three times as effective in the field."[46] Chloropicrin's comparatively poor diffusion created some gaps in what it could control; against root-knot nematodes, for example, its efficacy was highly dependent on their life cycle stage and depth in the soil, as it was ineffective at penetrating the root galls[47] they created.[48] It was also expensive enough that it was necessary to cover fumigated soil and seed beds to prevent off-gassing, typically through the use of glue-coated paper.[49]

While chloropicrin fumigation was always relatively expensive, alternatives became increasingly necessary as existing stockpiles were drawn down and the cost of chloropicrin became prohibitive. In 1935, fumigation with chloropicrin cost $125 per acre; by 1941, it had risen to $200 or $300, becoming economically unviable for all but the most valuable crops and causing a temporary lull in commercial fumigation until the early 1940s.[50] The rapid development and introduction of synthetic pesticides in the mid-20th century included several new fumigants, including D-D mixture, ethylene dibromide (EDB), and dibromochloropropane (DBCP). D-D mixture, a compound of 1,2-dichloropropane and 1,3-dichloropropene, was a byproduct of Shell Company's production of allyl chloride, was introduced in Hawaii in the early 1940s as a potent nematicide and insecticide. EDB, a component of anti-knock gasoline additives, was introduced to agriculture in 1945. EDB was primarily a nematicide - likely the most potent by volume available to growers - and became one of the most widely-used pre-plant soil fumigants by 1960. DBCP, another nematicidal fumigant introduced in 1955, was a less phytotoxic alternative to D-D mixture or EDB; it could be used for nematode control in cropped soil without injuring the plants.[51,52,53] Compared to chloropicrin, these fumigants were more limited in their spectrum of control, but were easier to handle, could be applied without a soil cover, and did not possess the lachrymal effect associated with chloropicrin vapors. They were also substantially less expensive - D-D mixture, for example, cost $35 to $90 an acre in 1955 - and made soil fumigation economically viable for a much

[42] A. Taylor, "Nematocides and Nematicides - A History", pp. 226–227.
[43] Lear, "Use of Methyl Bromide and Other Volatile Chemicals for Soil Fumigation", pp. 3–4.
[44] Roark, *A Bibliography of Chloropicrin, 1848-1932*, pp. 1–2.
[45] Lembright, "Soil Fumigation: Principles and Application Technology", pp. 632–633.
[46] Newhall, "Disinfestation of Soil by Heat, Flooding, and Fumigation", p. 232.
[47] Galls are abnormal plant growths created by insects in which an larva develops.
[48] Stark, "Investigations of Chloropicrin as a Soil Fumigant", pp. 954–963.
[49] Newhall, "Disinfestation of Soil by Heat, Flooding, and Fumigation", pp. 209–210.
[50] Lear, "Use of Methyl Bromide and Other Volatile Chemicals for Soil Fumigation", pp. 2–4.
[51] Newhall, "Disinfestation of Soil by Heat, Flooding, and Fumigation", pp. 214–219.
[52] Lear and Akesson, "Chemical Control of Nematodes", pp. 25–26.
[53] Babich, D. Davis, and Stotzky, "Dibromochloropropane (DBCP): A Review", pp. 208–209.

greater selection of crops. However, like many of the synthetic compounds developed in the mid-20th century, these three fumigants were later discovered to be environmentally persistent toxins with chronic, long-term health effects; the EPA would ban EDB and DBCP by the early 1980s, and the D-D mixture had to be reformulated.[54]

There are two particularly salient parallels between the history of these nematicides and the broader narrative of strawberry production. The first is that the impetus behind adopting soil fumigation in the pineapple industry mirrors that of strawberries; that is, fumigation for nematode control was a response to the rotations required by pineapple production. Pineapple growers had found it difficult to maintain the health of their soil as organic amendments decomposed rapidly in the Hawaiian climate, and had experienced a gradual decline in productivity attributed to nematode infestations. While growers could reduce nematode density by fallowing for two years, rotations with other truck crops appear to have been ineffective; permanent cultivation of pineapples thus depended on control of the nematode population.[55,56] The second is the adoption pattern of nematicidal fumigation, which closely resembles the adoption of fumigation in strawberries we will discuss in Chapter 8. Following the success of D-D and ethylene dibromide, both the Shell Company and Dow Chemical Company began marketing nematicidal fumigation treatments in the continental U.S. through field demonstrations on experimental plots.[57] This was a time-intensive process, as the existence of nematodes first had to be proven to farmers, and then the nematicide itself had to be established as an effective treatment. This required multiple seasons: at least one to demonstrate positive yield increases, and the rest as farmers performed their own independent trials. Early adopters tended to be wealthier or otherwise less risk averse than their peers, who began their own adoption process after observing the results. In total, nematicidal fumigation took roughly eight years from first demonstration to widespread use in agricultural communities.[58]

6.3.2 Methyl Bromide

Methyl bromide would first enter agricultural use in the 1930s, though laboratory production dates back at least as far as 1885.[59] In the 1890s, methyl bromide was employed in medicine as a method of destroying cancerous tissue, and, somewhat distressingly, as an anesthetic agent in dentistry. By the 1920s, methyl bromide had been used in the manufacturing of dyes and was briefly considered as a potential refrigerant. As a heavy and nonflammable gas, it was also adapted for use as the chemical agent in handheld fire extinguishers, particularly in Europe, where it remained popular until the 1940s. It saw continued use as an extinguishing agent in British military aircraft for a few decades afterwards. In the United States, however, reports of its highly toxic nature limited its adoption compared to other

[54] D-D and EDB were found to contaminate groundwater, and DBCP had severe adverse effects pertaining to human reproduction.

[55] W. Carter, "Soil Treatments with Special Reference to Fumigation with D-D Mixture", pp. 35–36.

[56] W. Carter, *Fumigation of Soil in Hawaii*, pp. 126–128.

[57] G. Thorne, *Principles of Nematology*, pp. 28–30.

[58] A. Taylor, "Nematocides and Nematicides - A History", pp. 227–229.

[59] Carnelley, "The Periodic Law", p. 500.

contemporary chemicals.[60,61]

Methyl bromide was not originally intended to be used as an agricultural fumigant, but was instead part of a series of experiments by Le Goupil (1932) to find suitable chemicals to use alongside ethylene oxide. Ethylene oxide had proven to be an effective space fumigant, but its flammability made it dangerous to use without a flame-retardant amendment.[62,63] Le Goupil discovered that a mixture of ethylene oxide and methyl bromide was an unexpectedly potent insecticide, and then that the methyl bromide itself was more potent than the ethylene oxide. Le Goupil would present his results to the Agricultural Academy in France in 1932; by 1934, methyl bromide fumigation was underway in several major French harbors.[64] Entomological and agricultural research of methyl bromide continued through the 1930s, initially in France but soon spreading westward to the United States and Canada. French entomologists Vayssiere (1934), De Francolini (1935) and Lepigre (1936, 1938) are frequently credited as the first to engage in their own fumigation experiments on pests in cereal and milling grains. In 1935, D. B. Mackie of the California Department of Agriculture performed the first insecticidal application of methyl bromide recorded in California. Like Le Goupil, Mackie originally sought a less combustible alternative to current fumigants, and believed that the use of methyl bromide in quarantine fumigation would "[provide] a greater freedom of movement for many [quarantined] products." In 1936, he would speak with both the United States and the Canadian Department of Agriculture to promote collaboration on quarantine treatments as well as further testing on economically-relevant pests, including Japanese beetles, European corn borers, and oriental fruit moths. He would go on to develop a new dispenser (the Mackie-Carter applicator) capable of fumigating with unadulterated methyl bromide; previously, these mechanical limitations had been circumvented with the addition of carbon dioxide. Methyl bromide proved to be extremely effective at controlling several agricultural pests, and was successfully employed against rats (Mackie and Carter, 1936), tuber moths (Mackie, 1936), and ground squirrels (Berry, 1938). It also had potential value for public health, specifically in the suppression of sylvatic plague (Stewart and Mackie, 1938), as fumigation controlled both rodents as well as fleas at all stages of development.[65,66]

6.3.3 Japanese Beetle Quarantine, 1930s

Production of methyl bromide increased considerably between 1935 and 1940, as did its role in quarantine fumigation. Notably, methyl bromide was one of the most effective methods of curbing the spread of the Japanese beetle, a invasive and highly destructive species which had been discovered in a New Jersey nursery in 1916. It caused significant economic damage to agricultural production, and the geographic range over which the beetle had become established grew larger further every year; rail and truck shipments of agricultural goods were often unwitting sources of new infestations. In 1920, the federal government established a

[60] Henning, *Patent: Fire-Extinguishing Composition.*

[61] Alexeeff and Kilgore, "Methyl Bromide", pp. 102–106.

[62] Back, Cotton, and Ellington, "Ethylene Oxide as a Fumigant for Food and Other Commodities", pp. 226–229.

[63] Le Goupil, "The Insecticidal Properties of Methyl Bromide (trans.)"

[64] Fleming, *Preventing Japanese Beetle Dispersion by Farm Products and Nursery Stock*, pp. 9–10.

[65] Stewart, "The Use of Methyl Bromide as a Fumigant", pp. 153–155.

[66] D. Mackie, "Methyl Bromide - Its Expectancy as a Fumigant", pp. 70–74.

quarantine over a significant portion of the eastern United States, which included the restriction of interstate agricultural commerce during the beetle's annual emergence - typically between May and October, depending on location. States imposed their own restrictions on agricultural shipments within their own borders. Forage crops, hay, and straw shipments were completely prohibited from infested farms during the beetles' emergent period due to the risk of transference.[67,68]

There was no established precedent for quarantine treatment prior to the 1920s; physical inspection, despite the unsatisfactory rate of identification, was the only authorized method of quarantine control for several years. However, as the range of affected areas grew, the volume of shipments exceeded available labor supply and limited the number of the inspections to products thought most likely to be carriers.[69] Prior to 1924, inspections were performed on individual farms; after 1924, shipments underwent examination at centers set up throughout the affected area. As the territory of the Japanese beetle expanded, so too did the number and geographical spread of these centers. Several alternative methods were explored as a way to improve efficacy and reduce demands on quarantine inspectors; this included chemical treatments with carbon disulfide, hydrocyanic acid, and ethylene dibromide, as well as non-chemical methods such as mechanical removal and heat sterilization. Fumigation was effective but required limits on the duration of the treatment; longer exposure would ensure greater mortality, but excessive delay could reduce the value of marketed produce. Fumigation schedules for fresh produce were often limited to two or three hours. Required time for chemical treatments could be reduced by increasing dosages or temperatures, but both adjustments presented an increased risk of damaging the produce. Carbon disulfide and hydrocyanic acid could achieve 100 percent control within the allotted time, though efficacy declined in lower temperatures; carbon disulfide in particular required temperatures to be over 21°C. Ethylene dibromide, while eventually lethal, took between 2 and 5 days to actually kill treated beetles.[70] For non-chemical treatments, there was significant difficultly in scaling them up effectively, and they were unlikely to eliminate all beetles present in the shipment.[71,72]

Methyl bromide was adapted for beetle fumigation in the mid-1930s, and would resolve many of the issues with physical inspection. The process was easily scaled to different operational sizes, as the mechanism itself was simple and required minimal time to set up and operate: methyl bromide was pumped through a spray nozzle attached to the intake of a fan or blower, and was circulated inside of a train compartment or truck for up to 20 minutes. A single application was lethal to all stages of the Japanese beetle within the given two to three hour window, and at approved dosages the vast majority of transported plants and agricultural products were unharmed.[73,74,75] In both vault and railcar fumigation,

[67] Dudley et al., "Studies on Foodstuffs Fumigated with Methyl Bromide", pp. 2251–2252.

[68] Fleming, *Preventing Japanese Beetle Dispersion by Farm Products and Nursery Stock*, pp. 1–3.

[69] This included (at various points in time) corn, cabbage, lima beans, peaches, apples, raspberries, and blackberries.

[70] Fleming, *Preventing Japanese Beetle Dispersion by Farm Products and Nursery Stock*, pp. 4–19.

[71] Donohoe, A. C. Johnson, and Bulger, *Methyl Bromide Fumigation for Japanese Beetle Control*, pp. 296–297.

[72] Dudley et al., "Studies on Foodstuffs Fumigated with Methyl Bromide", pp. 2251–2252.

[73] Donohoe and V. A. Johnson, *The Effect on Plants of Methyl Bromide Fumigation.*

[74] Fleming, *Preventing Japanese Beetle Dispersion by Farm Products and Nursery Stock*, pp. 14–17.

[75] Donohoe, A. C. Johnson, and Bulger, *Methyl Bromide Fumigation for Japanese Beetle Control*, pp. 297–300.

methyl bromide remained effective regardless of load distribution or volume occupied, and its pesticidal action was not impeded by produce packaging or the soil balls of nursery shipments. It was also approved for usage in refrigerated cars and trucks as it maintained lethality even in low temperatures, only requiring alterations in the applied dosage. Methyl bromide's adoption reduced both the demand on personnel as well as the risk of human error, and fumigation became increasingly common as a method of beetle control; between 1938 and 1939, almost 4,000 railcars had been treated commercially. By 1942, this figure had risen to almost 10,000 carloads of produce, and methyl bromide had entirely replaced manual inspection for peppers, blueberries, apples, and white potatoes.[76,77,78]

6.4 Strawberry Fumigation with MB/Pic

The use of chloropicrin/methyl bromide fumigation to control *V. dahliae* was the culmination of several successive experiments performed in the early to mid-1950s. Wilhelm and Ferguson (1953) evaluated numerous fungicides under field conditions against verticillium wilt; of their selections, just three were found to effectively control the fungus, and of those three only chloropicrin diffused adequately throughout the soil.[79] A subsequent paper by Wilhelm and Sciaroni (1954) applied these results to the production of chrysanthemums. Population growth in San Mateo and Santa Clara had absorbed land previously available for chrysanthemum cultivation; in turn, growers had shortened or eliminated rotations in favor of continuous cropping. This led to a substantial increase in local *Verticillium* density and the severity of the resulting wilt outbreaks.[80] This was further complicated by the use of cuttings as new planting stock which could carry the fungus to clean soil, as well as the buildup of inoculum even when resistant varieties were cultivated.[81] Laboratory trials of chloropicrin demonstrated effective control over *V. dahliae* despite the rudimentary application methods; at the highest dosage, incidence of wilt was decreased by 90 percent. Estimated returns were also high enough to offset the cost, which fell between $450 and $650 per acre for the chemical alone. However, though field performance for early commercial adopters was promising, it was also comparatively inconsistent, which the authors attributed to unfamiliarity with chloropicrin fumigation. In later work, Wilhelm also pointed out that chloropicrin was unable to penetrate dead plant matter prior to decomposition, potentially leaving behind reservoirs for soil re-infestation.[82] Wilhelm and Koch (1956) adapted these chrysanthemum experiments for strawberries, parceling out an experimental plot and fruiting it for two years. Growth in the treated section was "exceptional," as was the overall yield effect; first and second-year yields were 9.8 and 16.7 tons per acre, respectively, more than double that of the 4 and 7.6 tons from the controls.[83]

In 1957, less than a year after the California Strawberry Advisory Board published the

[76] Donohoe, *Development of New Methyl Bromide Fumigation Schedules for Use Against Japanese Beetles*, pp. 260–262.
[77] *History of the Rutgers Entomology Department: Japanese Beetle Quarantine.*
[78] Donohoe, A. C. Johnson, and Bulger, *Methyl Bromide Fumigation for Japanese Beetle Control*, p. 302.
[79] S. Wilhelm and Ferguson, "Soil Fumigation Against Verticillium Albo-Atrum", pp. 593–595.
[80] S. Wilhelm and Sciaroni, "Verticillium in Chrysanthemum", pp. 9–10.
[81] Butterfield, *Chrysanthemum Culture in California*, pp. 1–2, 18–21.
[82] S. Wilhelm, *Bringing Our Knowledge Up to Date on Soil Fumigation, 2.*
[83] S. Wilhelm and Koch, "Verticillium Wilt Controlled", pp. 3, 14.

first fumigation schedule for chloropicrin, preliminary fumigation trials with methyl bromide and chloropicrin mixtures were underway. This was not a novel idea; Stark, Lear, and Newhall (1944), experimenting with nematicidal fumigation a decade prior, suggested that these chemicals would act as complements if applied in unison. Though chloropicrin was a potent fungicide, it was less effective against weeds and nematodes, and the inclusion of methyl bromide was expected to compensate for these deficiencies.[84] Their results demonstrated that MB/Pic was indeed an effective nematicide, but its overall applicability was questionable as the mixture was several times more expensive than alternative, non-chloropicrin-based fumigants. There were also issues in the application itself; the highly noxious chloropicrin was unpleasant to apply via hand fumigator, while the addition of methyl bromide made the mixture "difficult to handle," requiring new, less permeable methods of sealing the soil post-treatment.[85]

By the mid-1950s, large strides had been made in fumigant application. The adoption of tractor-mounted fumigation equipment - applicators known as "chisels" - had improved treatment precision and provided a much-needed separation between the fumigator and the chemical. New polyethylene production methods allowed tarping with plastic sheets, a far less permeable method of post-fumigation sealing of the soil. The resulting increase in fumigation efficacy lowered the necessary application rate of chloropicrin from 480 to 320 pounds per acre, and an associated cost reduction of $150 per acre was expected to fully cover additional expenditures on tarps and attendant labor.[86] Critically, polyethylene was also impermeable enough to permit the addition of methyl bromide, typically included in a 2:1 ratio of chloropicrin to methyl bromide and applied at the same rate of 320 pounds per acre. This MB/Pic mixture demonstrated equivalent control over verticillium wilt along with a broad spectrum of other pests, all at a modest cost reduction - methyl bromide was 10 to 15 percent less expensive than chloropicrin. The inclusion of methyl bromide also generated a more potent growth response and allowed for more flexibility in treatment; the chemical ratio could be altered if fungal pest pressure was low, often the case on land that had been recently fumigated.[87] It was, however, still cost-prohibitive at $300 to $350 per acre, limiting its adoption to where damage control was sufficiently remunerative: profitable crops subject to high pest pressure and lacking alternative methods of control. Strawberry production, specifically in California, fulfilled these criteria; by 1962, pre-plant MB/Pic fumigation was in general use in southern California, and by 1965 Wilhelm and Paulus suggest it had become standard practice for virtually 100 percent of new acreage in the state.[88,89,90]

[84] S. Wilhelm, *Progress in Controlling Verticillium Wilt by Soil Fumigation.*

[85] Stark, "Investigations of Chloropicrin as a Soil Fumigant", pp. 957–964.

[86] S. Wilhelm, *Bringing Our Knowledge Up to Date on Soil Fumigation, 4.*

[87] S. Wilhelm, Paulus, and McCain, *Bringing Our Knowledge Up to Date on Soil Fumigation.*

[88] S. Wilhelm, R.C. Storkan, and J.E. Sagen, "Verticillium Wilt of Strawberry Controlled", pp. 744–747.

[89] Bain and Hoos, *The California Strawberry Industry*, p. 77.

[90] S. Wilhelm and Paulus, "How Soil Fumigation Benefits the California Strawberry Industry", pp. 267–268.

Chapter 7

Fumigants and Monoculture: A Model

As discussed in Chapter 5, the combination of the replant problem and verticillium wilt had led Californian strawberry growers to adopt a culture based around regular migration. It took several years for the soil to return to a suitable condition, and there were few crops that could be grown in rotation with strawberries that would not also promote *V. dahliae*. MB/Pic fumigation provided an alternative option to growers: an expensive treatment that allowed them to cultivate the same crop repeatedly in the same location. It should be emphasized that rotation did not disappear with fumigation, as strawberry growers would - and still do - perform short, single-season rotations with a small number of other, similarly high-value crops. In essence, however, farmers elected to adopt monocultural cultivation practices, and strawberry production became near-continuous under soil fumigation.

Agronomy and related fields have long emphasized the importance of crop rotation as part of effective soil maintenance and land stewardship. Yet, as California strawberry production suggests, there are significant economic advantages to monoculture, not the least of which was the sustained increase in productivity from 1960 onward. The current system is highly capital intensive, both on-farm (drip irrigation, plasticulture, chemical application) and off-farm (cooling, shipping). Minimizing the time between producer and processor remains critical, and capital expense and distance constraints have encouraged growers to increase the size of their farms in order to benefit from economies of scale in production technology.[1] The existing monoculture system was until 2017 predicated on and facilitated by methyl bromide, but alternatives are so far unable to replicate the same efficacy. Methyl bromide regulation is therefore potentially destabilizing, particularly as new or otherwise previously-controlled soil diseases - such as charcoal rot and fusarium - are becoming increasingly prevalent.[2,3]

In the following section, we will develop an economic model that tries to capture the features of the California strawberry industry. Specifically, we will examine the economic forces that lead growers to adopt monoculture in an industry that requires extensive capital investment but that cannot persist in the same location.

[1] *Interview with Gregory House, UC Davis.*
[2] *Interview with Steven Fennimore, UC Davis.*
[3] *Interview with Roger Hamamura, Planasa Nursery.*

7.1 Model

Our representative farmer cultivates a single unit of land and has the choice between their "target" crop of high value and a generic, lower-value alternative. We use strawberries as this representative target crop, and assume that after a single season of planting there is sufficient pest pressure to affect yields if the field is replanted. A farmer can reduce this pest pressure by either applying chemical damage control or rotating the field into production of the generic lower value crop for some period of time. We use wheat as a generic representative for all low value crops in the rotation. Realistically, a rotation sequence would need to consist of a variety of crops (sorghum, barley, sugar beets, etc.), and deviation from the sequence would carry some cost. Incomplete rotation sequences between plantings might reduce yields, and the less intervening time between plantings the more severe the effect. It might also cause inefficiencies in agricultural scheduling, such as unused time between harvesting the first crop and sowing the next. We represent the grower's decision by allowing them to make a costless decision to switch between crops before the start of any period; however, choosing to grow strawberries before the sequence is complete results in zero profit.

We begin by defining our variables and indices:

Variables

1. Two crops, strawberries and wheat, indexed as superscripts by $i = s, w$.
2. Prices for strawberries and wheat: p^s, p^w. By definition, $p^s > p^w$, which holds $\forall t \in \{T\}$.
3. Time (agricultural seasons) indexed by $t = 1, 2, ..., T$.
4. Initial capital investment, k
5. Land quality, q, a fixed and exogenous variable bound between $q_L \leq q \leq q_H$.
   - This can be thought of as representing both natural conditions (soil, climate, water availability) as well as the benefits of location (nearby external capital).
6. Chemical control, applied at a fixed cost per acre z.
7. Interest rate r and discount rate $\delta = \frac{1}{1+r}$.
8. Number of sequential seasons between strawberry plantings, η; we also have $\eta \in \{\mathbb{Z}\}$, where $\mathbb{Z}$ is the set of integers.

Assumptions

1. Output only depends on land quality and capital.
2. Capital k represents a bundle that contains a multitude of choices that a farmer might make - irrigation technology, land preparation equipment, mechanized harvesting, etc.

3. The variable η is an exogenous integer that indicates the number of seasons before strawberry pest pressures return to some baseline; farmers must wait η years between each strawberry planting.
4. We set strawberry profit to zero in any period where the η constraint is binding.
5. Profit per acre of wheat π^w is independent of capital or quality.
6. Strawberry prices, land quality, and the cost of investment do not change over time.

For clarity, η can be thought of as a representation of pest pressure, but also as strawberry farmers' unwillingness to cultivate land they believed had the potential to host verticillium wilt. It is also worth emphasizing that η does **not** count the current season. If $\eta = 4$, for example, strawberries would be grown in a cycle where $t = (1, 6, 11, ...)$, i.e. a strawberry season followed by four seasons of wheat.

7.1.1 Setup

The production function for an acre of strawberries is given as:

$$Y^s = f(\mathbb{1}_\eta, q, k) \tag{7.1}$$

where $\mathbb{1}_\eta$ indicates whether or not strawberries are productive that season. We operate under the standard production assumptions with regards to marginal productivity:

$$\frac{\partial f^s}{\partial k}, \frac{\partial f^s}{\partial q} \geq 0 \tag{7.2}$$

$$\frac{\partial^2 f^s}{\partial^2 k}, \frac{\partial^2 f^s}{\partial^2 q} \leq 0 \tag{7.3}$$

The marginal effect of quality on the marginal productivity of capital depends on whether they are substitutes (less than 0) or complements (greater than 0):

$$\frac{\partial^2 f^s}{\partial k \partial q} \lessgtr 0 \tag{7.4}$$

To facilitate analysis, we normalize acreage to 1 and assume that $\exists (q, k)$ such that $\pi^s(q, k) \geq \pi^w$ whenever the η constraint does not bind. In addition, we incorporate chemical control as a means for growers to reduce the value of the η constraint to η_c until the next time strawberries are planted, where $0 \leq \eta_c < \eta$. At this juncture, a grower may generate one of three profits in any season:

Strawberries grown without fumigation:

$$\pi^s = p^s f(q, k) \tag{7.5}$$

Strawberries grown with fumigation:

$$\pi^s = p^s f(q, k) - z \tag{7.6}$$

Wheat:

$$\pi = \pi^w \tag{7.7}$$

Our representative farmer, cultivating on land quality q, will then choose the option with the greatest net present value.

There are a couple of important caveats to be made with regards to how this model reflects reality. The first is that, for simplicity, we have excluded the possibility of a yield effect from equation (7.6); while this is reasonable for most damage control methods, we have seen evidence that MB/Pic also generates a growth response. The effects of this are straightforward: fumigation would lead to an increase in $f(q, k)$ and thus a farmer's profit from adoption. Second, the η constraint assumes the benefits of fumigation end immediately with the next strawberry planting, which does not appear to be the case.[4] It also fails to differentiate between levels of pest pressure. In our estimation, however, η remains a reasonable approximation of farmer behavior: strawberries were almost never planted sequentially, while Wihelm and Paulus claim that all new plantings were fumigated post-1965.[5]

7.1.2 Rotation

For a farmer who chooses rotation instead of fumigation, strawberry and wheat production will occur in a cycle. As they are profit-maximizing and lack market power, they will use the entire acre for strawberries beginning in $t = 1$ and in every $\eta+1$ period thereafter; this allows us to group strawberry and wheat production into cycles of length $\eta + 1$ for convenience.

A finite planning horizon requires us to consider that changing η also increases the number of strawberry plantings within a given T. With planning horizon of length T and a cycle of η, there are $\lfloor \frac{T}{\eta+1} \rfloor$ of these periods in total, and potentially a remainder of a partial cycle. To eliminate the need for the floor function and make the equation more tractable, we will assume that initial planning horizons only incorporate full $\eta + 1$ season cycles; i.e., $\frac{T}{\eta+1} \in \mathbb{Z}$.

Condensing the discounted profits of the strawberry and wheat production cycle, we have:[6]

$$\Pi^s = \sum_{t=1}^{\frac{T}{\eta+1}} \delta^{(t-1)(\eta+1)} p f(q, k) \tag{7.8}$$

$$\Pi^w = \sum_{t=1}^{\frac{T}{\eta+1}} \delta^{(t-1)(\eta+1)} \left(\sum_{j=1}^{\eta} \delta^j \pi^w\right) \tag{7.9}$$

All together, our farmer's net present value is:

[4] Voth, Radewald, et al., "Effects of Successive Soil Fumigation with Methyl Bromide-Chloropicrin on Strawberry Replanting".

[5] S. Wilhelm and Paulus, "How Soil Fumigation Benefits the California Strawberry Industry", p. 268.

[6] For clarity, equation (7.9) first sums over the η non-strawberry seasons and then sums over the number of total cycles in the planning horizon.

$$\Pi^s = \sum_{t=1}^{\frac{T}{\eta+1}} \delta^{(t-1)(\eta+1)}(pf(q,k) + \sum_{j=1}^{\eta} \delta^j \pi^w) - k \tag{7.10}$$

where $k \geq 0$. We can rewrite equation (7.10) as a pair of geometric series using assumption (6). Recall that a finite geometric sum can be written as:

$$\sum_{r=0}^{n-1} a * b^r = a(\frac{1-b^n}{1-b}) \tag{7.11}$$

and let us define $h(\delta, T, \eta) = \frac{1-\delta^T}{1-\delta^\eta}$. We then have:

$$\Pi^s = h(\delta, T, \eta+1)pf(q,k) \tag{7.12}$$

and:

$$\Pi^w = h(\delta, T, \eta+1) * h(\delta, \eta, 1)\delta\pi^w \tag{7.13}$$

Optimizing our net present value under rotation is then given by:

$$\Pi = \max_k h(\delta, T, \eta+1)pf(q,k) + h(\delta, T, \eta+1) * h(\delta, \eta, 1)\delta\pi^w - k \tag{7.14}$$

For legibility, we will use subscripts to represent partial derivatives. Our first order condition is given as:

$$h(\delta, T, \eta+1)pf_k(q,k) - 1 = 0 \tag{7.15}$$

and the second order condition to determine a maximum is:

$$h(\delta, T, \eta+1)pf_{kk}(q,k) < 0 \tag{7.16}$$

A necessary condition for our farmer to engage in rotation is that our k^* satisfies $pf(q,k^*) > \pi^w$; otherwise, no strawberry production takes place. Assuming this k^* exists, we totally differentiate (15), solving for the comparative statics of price on capital investment. We have:

$$h(\delta, T, \eta+1)f_k(q,k^*)dp + h(\delta, T, \eta+1)pf_{kk}(q,k^*)dk = 0 \tag{7.17}$$

$$\frac{dk^*}{dp} = -\frac{f_k(q,k^*)}{pf_{kk}(q,k^*)} > 0 \tag{7.18}$$

Higher (lower) output price will necessarily increase (decrease) the initial level of investment, which carry through to our representative farmer's profits. Through k, it will also increase output itself:

$$\frac{dY}{dp} = f_k(q,k)\frac{dk}{dp} = -\frac{f_k(q,k^*)^2}{pf_{kk}(q,k^*)} > 0 \tag{7.19}$$

It is also worthwhile to consider the impact of land quality on capital decisions based on whether quality and capital are substitutes ($\frac{\partial f^2(q,k)}{\partial k \partial q} < 0$) or complements ($\frac{\partial f^2(q,k)}{\partial k \partial q} > 0$).

Different aspects of land can affect this relationship in opposing ways; improved soil water retention may lower irrigation capital requirements, while high soil fertility will increase the value of irrigation. From (7.15), we have:

$$\frac{dk^*}{dq} = -\frac{f_{kq}(q,k^*)}{f_{kk}(q,k^*)} \tag{7.20}$$

As the right hand denominator is negative, the sign of $\frac{\partial k^*}{\partial q}$ depends on the sign of f_{kq}. Necessarily, an increase in land quality will increase profits:

$$\frac{d\Pi}{dq} = h(\delta, T, \eta+1)pf_q(q,k) > 0 \tag{7.21}$$

but there is also the unusual case where a marginal increase in land quality might lower output:

$$\frac{dY}{dq} = \underbrace{f_q(q,k^*)}_{+} + \underbrace{f_k(q,k^*)\frac{dk}{dq}}_{-} \tag{7.22}$$

which may occur if land quality and capital are substitutes and the marginal increase from quality is less than the savings from reducing capital. Higher interest rates will also reduce output through their effect on investment:

$$h_\delta(\delta, T, \eta+1)pf_k(q,k)\frac{\partial \delta}{\partial r}dr + h(\delta, T, \eta+1)pf_{kk}(q,k)dk \tag{7.23}$$

$$\frac{dk}{dr} = -\underbrace{\frac{h_\delta(\delta, T, \eta+1)pf_k(q,k)\frac{\partial \delta}{\partial r}}{h(\delta, T, \eta+1)pf_{kk}(q,k)}}_{+} \tag{7.24}$$

where:

$$h_\delta(\delta, T, \eta+1) = \frac{\partial}{\partial \delta}\frac{1-\delta^T}{1-\delta^{\eta+1}} = \frac{(-T\delta^{T-1})(1-\delta^{\eta+1})}{(1-\delta^{\eta+1})^2} + \frac{(\eta+1)(1-\delta^T)\delta^\eta}{(1-\delta^{\eta+1})^2} \tag{7.25}$$

and $\frac{h_\delta}{h}$ can be written as:

$$\frac{h_\delta(\delta, T, \eta+1)}{h(\delta, T, \eta+1)} = \frac{1-\delta^{\eta+1}}{1-\delta^T}h_\delta = \frac{T\delta^{T+\eta} - T\delta^{T-1} + (\eta+1)\delta^\eta - (\eta+1)\delta^{T+\eta}}{(1-\delta^T)(1-\delta^{\eta+1})} \tag{7.26}$$

As h, h_δ, $f_k > 0$ and f_{kk}, $\frac{\partial \delta}{\partial r} < 0$, we positively sign both numerator and denominator.

Investment and output are also affected by our planning horizon and rotation cycle length. Although our time and rotation length are discrete, it is intuitive that $\frac{\Delta \Pi}{\Delta \eta} < 0$; if pests are more persistent, there will be a longer gap between strawberry plantings. At minimum, this will cause future strawberry production to occur later in time, and thus discount its value. Since we are considering finite time, there will also be a discontinuous decrease when a change in η reduces the number of strawberry periods for a given T. We can derive this directly by allowing $T \Rightarrow \infty$, which we will examine in a later section. The greater the difference between π^s and π^w, the more negative the effect. In addition, $\frac{\Delta k}{\Delta \eta} < 0$; as a larger η requires more time to elapse between each strawberry period, the marginal value of capital decreases.

7.1.3 Fumigation

The net present value for a farmer choosing to fumigate is given as:

$$\Pi = \max_k \sum_{t=1}^{T} \delta^{t-1}(pf(q,k) - Z) - k \tag{7.27}$$

The first and second order conditions are similar to (7.15) and (7.16), except now $\eta = 0$:

$$h(\delta, T, 1)p\frac{\partial f(q,k)}{\partial k} - 1 = 0 \tag{7.28}$$

$$h(\delta, T, 1)p\frac{\partial^2 f(q,k)}{\partial^2 k} < 0 \tag{7.29}$$

Since $\forall \eta > 0$ we have $\frac{1-\delta^T}{1-\delta} > \frac{1-\delta^T}{1-\delta^{\eta+1}}$, this indicates optimal investment is higher under a fumigation regime. For strawberry cultivation to take place, it must also satisfy:

$$pf(q,k^*) - z > \pi^w \tag{7.30}$$

Several comparative statics results - (7.18), (7.19), (7.20), and (7.22) - are identical between rotation and fumigation, so we omit them for brevity. The effect of interest rates on capital investment is:

$$\frac{dk}{dr} = -\underbrace{\frac{h_\delta(\delta, T, 1)pf_k(q,k)\frac{\partial \delta}{\partial r}}{h(\delta, T, 1)pf_{kk}(q,k)}}_{+} \tag{7.31}$$

where:

$$h_\delta(\delta, T, 1) = \frac{\partial}{\partial \delta}\frac{1-\delta^T}{1-\delta} = \frac{(T-1)\delta^T - T\delta^{T-1} + 1}{(1-\delta)^2} \tag{7.32}$$

and:

$$\frac{h_\delta(\delta, T, 1)}{h(\delta, T, 1)} = \frac{1-\delta}{1-\delta^T}h_\delta = \frac{(T-1)\delta^T - T\delta^{T-1} + 1}{(1-\delta)(1-\delta^T)} \tag{7.33}$$

Note that (7.33) is equivalent to (7.26) if $\eta = 0$; as (7.33) is decreasing in η, it holds that higher interest rates will have a greater negative impact on investment under fumigation.

A marginal increase in land quality will also have a greater impact on profits, as:

$$\frac{d\Pi}{dq} = h(\delta, T, 1)pf_q(q,k) > h(\delta, T, \eta+1)pf_q(q,k) \tag{7.34}$$

and naturally, profits will decline as the cost of fumigation increases:

$$\frac{d\Pi}{dz} = -h(\delta, T, 1) < 0 \tag{7.35}$$

As there is no rotation cycle, we can derive the effect of a longer planning horizon directly. In particular, a longer horizon will increase the level of investment. Using equation (7.28), we have:

$$h_T(\delta, T, 1)pf_k(q,k)dT + h(\delta, T, 1)pf_{kk}(q,k)dk = 0 \tag{7.36}$$

$$\frac{dk}{dT} = -\frac{h_T(\delta, T, 1)f_k(q,k)pf_k}{h(\delta, T, 1)f_{kk}(q,k)} = \frac{\delta^T ln(\delta) f_k}{1-\delta^T f_{kk}} > 0 \tag{7.37}$$

which holds as $ln(\delta)$ and f_{kk} are both negative. Through k, this also means that $\frac{dY}{dT} > 0$.

This result is of particular interest with regards to our historical narrative. While the planning horizon was implicitly held constant between our rotation and fumigation models, relocation imposed a four to five-year lifespan on any immobile/non-transferable equipment or investment. The preceding result indicates that even though relocation allowed growers to continue cultivating strawberries instead of rotating to lower-value crops, it was still reducing their total output through other channels. This also implies that strawberry cultivation would have been generally predisposed to sharecropping arrangements even in the absence of racial discrimination, as land rental provided access to capital that was otherwise unavailable.

7.1.4 Farmer's Choice of Strategy

From above, our representative farmer has three potential cultivation strategies - fumigation, rotation, or the alternative crop - and will choose the one that maximizes net present value; any parameter changes that affect the profit of strawberry production relative to the alternative or of fumigation relative to rotation will necessarily affect the farmer's decision. We indicate cultivation practices with subscripts, where Π^W, Π^R, Π^F indicate the net present value of wheat, rotation, and fumigation respectively, and k^R, k^F represent the optimal capital under rotation and fumigation.

An increase in the price of strawberries will naturally increase the likelihood of producing strawberries, potentially causing wheat to drop out entirely. It will also increase the adoption of fumigation:

$$\frac{\partial(\Pi^F - \Pi^R)}{\partial p} = h(\delta, T, 1)f(q, k^F) - h(\delta, T, \eta+1)f(q, k^R) > 0 \tag{7.38}$$

Relative to rotation, an increase in wheat profits will decrease the likelihood of adopting fumigation and increase the likelihood of adopting wheat:

$$\frac{\partial(\Pi^F - \Pi^R)}{\partial \pi^w} = -h(\delta, T, \eta + 1)h(\delta, \eta, 1) < 0 \tag{7.39}$$

$$\frac{\partial(\Pi^W - \Pi^R)}{\partial \pi^w} = h(\delta, T, 1) - h(\delta, T, \eta + 1)h(\delta, \eta, 1) > 0 \tag{7.40}$$

For clarity, equation (7.40) can also be written as:

$$\frac{\partial(\Pi^W - \Pi^R)}{\partial \pi^w} = \frac{1 - \delta^T}{1 - \delta} - \frac{1 - \delta^T}{1 - \delta^{\eta+1}} \frac{1 - \delta^\eta}{1 - \delta} \tag{7.41}$$

In most cases, an increase in land quality will increase the likelihood of adopting fumigation:

$$\frac{\partial(\Pi^F - \Pi^R)}{\partial q} = h(\delta, T, 1)pf_q(q, k^F) - h(\delta, T, \eta + 1)pf_q(q, k^R) > 0 \tag{7.42}$$

which holds as long as q and k are complementary. A reduction in η instead increases the likelihood of adopting rotation relative to either fumigation or alternative production, as:

$$\frac{\Delta \Pi^R}{\Delta \eta} < 0, \frac{\Delta \Pi^F}{\Delta \eta}, \frac{\Delta \Pi^W}{\Delta \eta} = 0 \tag{7.43}$$

7.2 Extension to Variable Inputs

We can also examine the model with the addition of variable input, although this adds a layer of complexity and requires us to consider the farmer's decision-making process. As before, the farmer operates within an agricultural planning horizon T and maximizes net present value by choosing an initial capital investment at $t = 1$. Once a capital investment is chosen, we assume that it remains until T and cannot be altered. We will again assume that wheat profits are a constant π^w and are unaffected by capital, input, or land quality. The farmer will therefore only make variable input decisions at the beginning of any period they choose to grow strawberries. We maintain the same assumptions from the previous section, and also assume that:

$$\frac{\partial f}{\partial x} > 0, \frac{\partial^2 f}{\partial^2 x} < 0 \tag{7.44}$$

It is possible that input could act as either a substitute or complement for both land quality and capital:

$$\frac{\partial^2 f}{\partial x k}, \frac{\partial^2 f}{\partial x q}, \lesseqgtr 0 \tag{7.45}$$

In effect, a farmer is making their decision of x_t and k in two stages. First, they choose an optimal variable input path for each potential level (or bundle) of capital investment. Second, they choose the initial investment k that maximizes profits. We assume that our farmer operates under a rotation regime, giving us:

$$\Pi = \max_{x_t} h(\delta, T, \eta+1)(p_t f(x_t, q, k) - x_t) + h(\delta, T, \eta+1)h(\delta, \eta, 1)\pi^w - k \tag{7.46}$$

Note that each x_t decision is independent of the others - the choice of variable input is found by equating marginal productivity to marginal cost in any period. When strawberries are produced, the profit function that year is:

$$\Pi_t = \delta^{t-1}(p_t f(x_t, q, k) - x_t) \tag{7.47}$$

We will assume that the farmer's expectation of future prices at $t = 0$ are constant going forward; in other words, we have $p_i = p_j$, $\forall i, j \in T$. However, prices may deviate in future periods. Using subscripts to indicate partial derivatives, the first order condition for input in any period is:

$$p_t f_x(x_t, q, k) - 1 = 0 \tag{7.48}$$

The farmer then evaluates candidate values for initial capital given solution x_t^*:

$$\max_{k} h(\delta, T, \eta+1)(p_t f(x_t^*, q, k) - x_t^*) + h(\delta, T, \eta+1)h(\delta, \eta, 1)\pi^w - k \tag{7.49}$$

At x_t^*, the farmer equates marginal productivity of capital over all periods to its marginal cost:

$$h(\delta, T, \eta+1)p_t f_k(x_t^*, q, k) - 1 = 0 \tag{7.50}$$

Maximization requires the Hessian matrix to be negative semi-definite, so that our second order conditions fulfill:

$$p f_{xx}(x_t, q, k) < 0 \tag{7.51}$$

$$h(\delta, T, \eta+1)p f_{kk}(x_t, q, k) < 0 \tag{7.52}$$

$$f_{xx}(x_t, q, k) f_{kk}(x_t, q, k) - (f_{xk}(x_t, q, k))^2 \geq 0 \tag{7.53}$$

7.2.1 Comparative Statics of Variable Inputs

We begin by examining the effect of land quality on capital and variable input, suppressing functional arguments in derivatives for legibility. Totally differentiating our first order conditions in (7.47) and (7.49), we have:

$$p f_{xx} dx + p f_{xk} dk + p f_{xq} dq = 0 \tag{7.54}$$

and:

$$h(\delta, T, \eta+1)(p f_{kx} dx + p f_{kk} dk + p f_{kq} dq) = 0 \tag{7.55}$$

We are left with:

$$f_{xx} \frac{dx}{dq} + f_{xk} \frac{dk}{dq} = -f_{xq} \tag{7.56}$$

and:

$$f_{xk}\frac{dx}{dq} + f_{kk}\frac{dk}{dq} = -f_{kq} \tag{7.57}$$

which we solve via Cramer's Rule to find:

$$\frac{dx}{dq} = \frac{f_{xk}f_{kq} - f_{xq}f_{kk}}{f_{xx}f_{kk} - (f_{xk})^2} \tag{7.58}$$

and

$$\frac{dk}{dq} = \frac{f_{xq}f_{kx} - f_{xx}f_{kq}}{f_{xx}f_{kk} - (f_{xk})^2} \tag{7.59}$$

As the denominator for (7.58) and (7.59) is positive and both f_{kk} and f_{xx} are negative, $\frac{dx}{dq}$ and $\frac{dk}{dq}$ are positively signed if capital, input, and quality are complements and ambiguous if they are substitutes.

The comparative statics results are similar for price:

$$\frac{dx}{dp} = \frac{1}{p}\frac{f_{xk}f_k - f_{kk}f_x}{f_{xx}f_{kk} - (f_{xk})^2} \tag{7.60}$$

$$\frac{dk}{dp} = \frac{1}{p}\frac{f_{kx}f_x - f_{xx}f_k}{f_{xx}f_{kk} - (f_{xk})^2} \tag{7.61}$$

Again, the sign depends on the relationship between capital and input. However, these results are modeling a change in the farmer's **initial expectation** of strawberry prices; otherwise, capital investment is static. Necessarily, this means a price deviation after the initial period will lead to suboptimal production. For a change in price at time t, we have:

$$\frac{dx_t}{dp_t} = -\frac{f_x(x_t, q, k^*)}{p_t f_{xx}(x_t, q, k^*)} \tag{7.62}$$

Taking the difference between (7.59) and (7.61), we are left with:

$$\frac{dx}{dp} - \frac{dx_t}{dp_t} = \frac{f_{xk}(f_{xx}f_k - f_x f_{xk})}{f_{xx}(f_{xx}f_{kk} - (f_{xk})^2)} \tag{7.63}$$

The additional effect on variable input from keeping capital constant again depends on the relationship between capital and input. If they are complements, then farmers will respond to a change in price by using additional variable inputs relative to when capital is malleable; if substitutes, they will use less.

If we allow $T \Rightarrow \infty$, we can also derive the effect of rotation length on our choice variables. We have:

$$pf_{xx}dx + pf_{xk}dk + 0d\eta = 0 \tag{7.64}$$

$$\frac{1}{1-\delta^{\eta+1}}(pf_{kx}dx + pf_{kk}dk) + pf_k\frac{\delta^{\eta+1}ln(\delta)}{(1-\delta^{\eta+1})^2}d\eta = 0 \tag{7.65}$$

which we solve to find:

$$\frac{dx}{d\eta} = \frac{p^2 f_{xk} f_k \delta^{\eta+1} ln(\delta)}{(1-\delta^{\eta+1})^2 (p^2 f_{xx} f_{kk} - (p f_{xk})^2)} \lesseqgtr 0 \tag{7.66}$$

and

$$\frac{dk}{d\eta} = \frac{-p^2 f_{xx} f_k \delta^{\eta+1} ln(\delta)}{(1-\delta^{\eta+1})^2 (p^2 f_{xx} f_{kk} - (p f_{xk})^2)} < 0 \tag{7.67}$$

The sign of $\frac{dk}{d\eta}$ is unambiguously negative, while the sign of $\frac{dx}{d\eta}$ again depends on whether capital and input are complements or substitutes; rotation length affects variable input through its impact on capital investment.

7.3 Regional Production

From the initial comparative statics results, equation (7.42) suggests that the distribution of land quality among heterogeneous farmers will influence cultivation patterns, which we examine below. Assume each farmer owns a single acre of heterogeneous quality; it is still exogenously determined and all farmers are subject to the same η. Referring back to initial assumptions, quality falls over a range $q_L \leq q \leq q_H$, and, $\forall q^1 > q^2$:

$$f(x_t, q^1, k) > f(x_t, q^2, k) \tag{7.68}$$

Quality is continuously distributed with density function $\phi(q)$. With multiple actors, constant strawberry price is relaxed in favor of a downward-sloping, time-invariant demand curve. Profit for wheat remains constant; a low value crop is likely produced on a larger scale with less elastic demand.

Equation (7.42) suggests that production practices will be stratified by land quality:

- Fumigation will occur on land where $q_F \leq q \leq q_H$
- Rotation will occur on land where $q_R \leq q \leq q_F$
- The alternative crop is grown on land where $q_L \leq q \leq q_R$

In any period, the average strawberry supply for the region will take the form:

$$\int_{q^F}^{q^H} p(f) f(x_i, q_i, k_i) \phi(q) dq + \int_{q^R}^{q^F} \frac{h(\delta, T, \eta+1)}{\eta+1} (p(f) f(x_i, q_i, k_i)) \phi(q) dq \tag{7.69}$$

which is subject to $x_i, k_i \geq 0$, $0 < \delta < 1$, and the η constraint.

It is possible that demand for strawberries is sufficiently high that all land is used for strawberry production in $t = 1$; this would also require the farmer on the lowest land quality to benefit more from producing the Zth acre of strawberries in $t = 1$ rather than delaying production until $t = 2$. More realistically, Z is sufficiently large that supply and demand will reach equilibrium without dedicating all acreage to strawberry production. Holding all other variables constant, per-unit costs are cheaper on higher quality land as

$f(x, q^1, k) > f(x, q^2, k^*)\ \forall q^1 > q^2$. For farmers that fall into the rotation category, we would expect production to begin on the higher quality land and move to lower quality land in future periods; this will require an increasing amount of land over the course of the rotation cycle. A shorter η may extend the range of land qualities that adopt rotation by increasing relative profit, or instead remove low-quality land from production by allowing higher quality land to return to strawberries earlier.

Chapter 8

The Postwar Era

The reallocation of labor from agriculture to wartime industries during World War II caused strawberry production to decline on a national scale. The effects were especially pronounced in California, where acreage and production fell by 75 percent between 1940 and 1945. The internment of Japanese-Americans was devastating to the industry, compounding the existing shortage of labor and removing key personnel from farm management and growers' associations. Subsequent postwar recovery was slow in many states; most faced an anemic labor supply as well as consecutive seasons of drought and frost, and many would never return to their previous levels of production. California, however, recovered in short order; the state industry returned to its pre-war level of acreage by 1950, then entered a period of rapid expansion during which growers would bring an additional 1,000 to 3,000 acres under cultivation annually for the next several years. Between 1950 and 1957, strawberry cultivation in California underwent a fourfold increase in acreage and a threefold increase in yield, and state production comprised roughly 40 percent of the 500 million pounds of strawberries sold every year.[1]

Within California, agricultural innovations and tightening land constraints would have their own redistributive effects on strawberry cultivation. Of the roughly 5,000 acres of strawberries cultivated prior to WWII, slightly less than half were located in the interior districts of California, with the Sacramento/Florin district alone accounting for 1,100 to 1,300. Compared to coastal and southern producers, growers in the interior districts had balanced lower yields with lower costs of production and the longer duration of their plantings; Sacramento in particular leveraged slightly lower transportation costs to markets in the Pacific Northwest.[2] However, the Sacramento district never saw the post-war strawberry boom experienced by the rest of the state; increasing costs of production throughout the state and the introduction of higher-yielding varieties favored the Central Coast. By 1950, the Central Coast comprised half the acreage in the state, while the Sacramento district consisted of just 300 acres, or 6 percent.

8.1 Urbanization

Following the end of the war, in-migration to California occurred at a rate comparable to that of the Gold Rush, sufficient to nearly double the state population within twenty years. Towns

[1]Bain and Hoos, *The California Strawberry Industry*, pp. 22–25, 127–146.

[2]Thomas, *The Production of Strawberries in California*, pp. 14–26.

and cities in California that had historically been service centers for agricultural communities would also become population hubs following the influx of new residents. However, these centers were also situated on or in close proximity to fertile “Class I” or “Class II” type soils; their expansion encroached upon what was otherwise highly desirable agricultural land, absorbing it at an estimated rate of 100,000 to 500,000 acres annually. Increased demand would also drive up the market value from hundreds of dollars an acre to thousands; by the late 1950s, some single-acre parcels were on the market for $6,000.[3] Many growers chose to sell their land for financial gain as well as to avoid the tax burden associated with a new assessment of their land value. Low density suburban housing and the rise of the automobile/highway system exacerbated the effects of urban sprawl, fragmenting agricultural districts and creating additional hurdles in the production process. Nearby subdivisions represented additional resource constraints for growers, increasing the competition for local water as well as requiring additional land to be used as buffer zones separating residential areas them potentially hazardous farm activities - such as the spraying of pesticides. In addition, the intensification of petrochemical air pollution was now affecting crop health in nearby districts, with the smog from Los Angeles alone estimated to cause over $3 million of agricultural damage annually to surrounding farms.[4,5]

Intensifying competition for land altered the composition of agriculture, intensifying production and homogenizing crop selection as less valuable crops became economically unviable. The counties of Los Angeles, Orange, and San Bernardino led southern California in the increase of farm production value per cropland acre; not coincidentally, these counties were also closest to the region’s main urban centers.[6] Orange County, which experienced the highest rate of population growth in the state during the 1950s and 1960s, had fully 60 percent of its agricultural acreage converted to other uses by 1970, predominantly housing subdivisions and related infrastructure. Truck crop acreage, however, fell by just 20 percent thanks to a combination of categorically high gross income and by displacing field crops from land that had traditionally been used to cultivate them. Profitability did not solely determine the crop-specific impact of urbanization. Orchard acreage, for instance, was reduced by 75 percent, highly disproportionate with the relative value of their production but a reflection of how desirable the land they occupied was for residential development. Variety of both truck and orchard crops was pared down by intense selection pressure; by 1970, only avocado and citrus groves were operating commercially, and four crops - asparagus, celery, corn, and tomatoes - accounted for roughly 60 percent of truck crop acreage. Other counties with high population, like Santa Clara and Ventura, underwent similar changes: a reduction of field crop cultivation, less breadth in crop varieties, and a concentration of acreage into higher-value production.[7,8] Strawberries in particular became a major draw for growers during this period, and crop reports from several counties indicate they were siphoning acreage from other agricultural commodities.[9]

[3]Griffin and Chatham, “Urban Impact on Agriculture”, p. 202.

[4]Gregor, “Urban Pressures”, pp. 312–321.

[5]Griffin and Chatham, “Urban Impact on Agriculture”, pp. 195–203.

[6]Gregor, “A Map of Agricultural Adjustment”, pp. 16–17.

[7]Kerr, “Impact of Urbanization”, pp. 164–169.

[8]McCluskey and G. Goldman, *Agriculture in Ventura County*, pp. 4–23.

[9]For whatever reason, strawberries did not belong to a fixed category; they were sometimes included in truck crops, and

8.2 Postwar Innovation

8.2.1 The University Varieties

The strawberry yield gap between California and other states was widened in 1945 by the introduction of high-yielding varieties developed by the UC strawberry breeding program. The breeding program, initiated in 1926 and headed by W.T. Horne and A.G. Plakidas, sought to develop commercially-viable cultivars that possessed genetic resistance to disease as a means to resolve growers' ongoing struggle with xanthosis. The program's breeding efforts made extensive use of the California population of *F. chiloensis* as well as a series of *F. chiloensis* crosses developed by Albert Etter, all of which had been found to be either immune or asymptomatic to xanthosis.[10] Harold Thomas and Earl Goldsmith, who succeeded Horne and Plakidas in the 1930s, would introduce the culmination of the program's work in 1945: five cultivars - the University varieties - known as the Shasta, Lassen, Sierra, Tahoe, and Donner. They were not considered to be high-quality berries in terms of consumption, but they were productive, bore attractive fruit multiple times over long seasons, and performed well in the micro-climates of key strawberry districts. While none of the five were completely immune to xanthosis, all but the Donner possessed moderate to high resistance. Alongside the adoption of preventative cultural practices, including delayed planting schedules, isolation of nurseries and fields, and virus-free planting stock, this was sufficient protection to prevent yield loss from disease.[11,12]

The Lassen and Shasta were by far the most widely adopted of the five varieties. The Lassen, grown primarily in southern districts, tended to bear large crops of fruit periodically throughout the season, peaking up to three times between May and October. Lassen was the most productive of the varieties by a significant margin, with yields a full third greater than the second heaviest bearer, the Tahoe. The Shasta was most widespread in the Central Coast; although somewhat less productive and slightly smaller than the Lassen, it was both firmer and sweeter. The Shasta was also unusual in its bearing patterns; after its primary spring harvest, it would continue to bear a reduced quantity of fruit into the summer and the early fall.[13] By the early 1950s, yields in California had reached an unparalleled six to eight tons per acre, three to five times the national average. Similar results were difficult if not impossible to replicate elsewhere, as yields were heavily dependent on coastal climates. In Massachusetts, for example, the Shasta and Lassen entered production in June, and would yield a single crop before entering dormancy.[14,15]

8.2.2 Freezing

The immediate post-war period also marked California's entrance into the frozen strawberry market. The invention of the quick-freezing process at the end of the 1920s effectively created

at other times the orchard crop category was extended to include berries.

[10]Darrow, "Strawberry Improvement", p. 467.

[11]Thomas, *The Production of Strawberries in California*, pp. 3–5.

[12]Thomas, *Verticillium Wilt of Strawberries*, p. 5.

[13]Ibid., pp. 3–11.

[14]Bain and Hoos, *The California Strawberry Industry*, pp. 4–22.

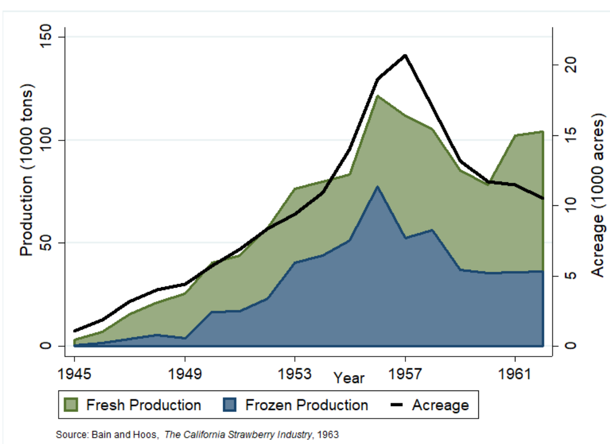
[15]Darrow, Scott, and G. F. Waldo, *Strawberry Varieties in the United States*, pp. 5–6.

a new product in "small-pack" frozen berries, intended for household use rather than food manufacturing. A seasonal luxury was now an everyday commodity; frozen strawberries were cheaper, could be stored indefinitely, and were available year-round. In 1941, national frozen production was estimated to be slightly greater than 73 million pounds, with per capita consumption at approximately half a pound annually. Further growth, however, was constrained by retailers and households' lack of frozen storage capacity; some preexisting cold storage equipment was converted into freezer space, but the majority had to be constructed from scratch.[16] The overwhelming majority of frozen production was supplied by the Pacific Northwest - between 65 and 90 percent through the late 1930s and early 1940s - as well as Louisiana, which would contribute a non-negligible fraction from 1941 onward. Sufficiently high prices in the fresh market, along with comparatively low costs of production in the Pacific Northwest, limited California's participation in the frozen market. According to Thomas, "at this time (1939), practically none of the crop is handled [by freezing]."[17]

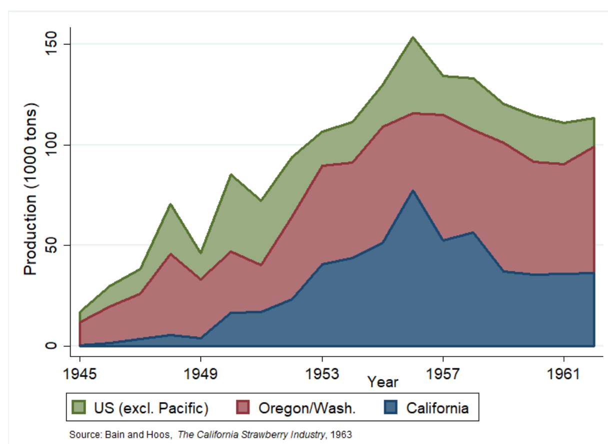
The frozen market was fundamentally restructured in the years following World War II thanks to significant changes in capital and consumption, with acreage and production patterns are visually represented in the graphs included in Figure 8.1. Figure 8.1(a) captures the rapid postwar expansion of the strawberry industry in California; the relative stability of fresh market production suggests that the increase in acreage was closely related to the growth of frozen production. Figure 8.1(b) shows the entirety of frozen production in the US; national trends closely mirrored those in California. The steep decrease in frozen production post-1957 will be addressed in the following section.

Figure 8.1: **Frozen Strawberries, 1945-1961**

(a) Frozen Production, California



(b) Total Frozen Production



*Prior to 1950, production was recorded in volume (crates), leading to measurement error after converting to weight.

Between 1945 and 1957, the capacity of refrigerated warehouses on the Pacific Coast increased by 47 million cubic feet; a similarly dramatic expansion was seen at both the

[16]Thomas, *The Production of Strawberries in California*, pp. 63–64.
[17]Ibid., p. 63.

retailer and consumer level.[18] Per capita consumption reached 1.5 pounds annually - roughly three times prewar levels - and national frozen pack was now in the neighborhood of 250 million pounds per year. Prices were buoyed by what was ostensibly perpetual growth in demand, and the frozen market had become a parallel to the fresh market rather than a surplus distress outlet.[19,20] For California, the market gap left by wartime decline and slow postwar recovery of strawberry acreage in other states had coincided with the release of the University varieties. Higher yields and disease resistance reduced per-unit production costs, while processors' lower size and quality requirements further mitigated disadvantages of prolonged strawberry plantings; strawberries intended for processing might be fruited for up to five years at a time. Extended seasons in California, particularly with the extended bearing of the Shasta, were key to consistent downstream supply. Long seasons were also valuable given the high fixed costs of processor freezing capacity and retailer storage, and processors in California were able to leverage them to specialize more heavily in strawberry production. Facilities were typically able to operate for much longer on strawberries alone, and longer seasons and greater throughput translated to larger and more efficient capital investments.[21,22]

Figure 8.2: **Processors, 1950s.**

Source: Reed, *Survey of the Pacific Coast*, 1957.

California processing plant distribution is shown in Figure 8.2, while the average characteristics of Pacific Coast facilities are provided in Table 8.1; operating days and total hours specifically refer to strawberry processing. The impact of season length on facility operation is self-evident. While a processing facility in California might devote up to six months to strawberries alone, processors in Washington and Oregon had to diversify their feedstock in order to reach similar uptime. Although data for Oregon is not available, average operation time per day is also 20 percent greater in California than Washington. A basic outline of a medium-sized facility is included in Figure 8.3. Given the equipment specificity, it is unlikely that strawberry processing capital was entirely interchangeable for other produce, making it reasonable to assume that feedstock diversity would also require broader capital investment.[23] From Table 8.2, as well as Figure 8.4, we can also see that the input capacity of strawberry processing increased almost twice as fast as the costs of equipment and operation.

[18]R. H. Reed, *Survey of the Pacific Coast*, p. 9.

[19]Bain and Hoos, *The California Strawberry Industry*, pp. 5–6, 39–41, 139–140.

[20]McDowell, "The Economic Impact of Technology on Strawberries", pp. 1788–1792.

[21]R. H. Reed, *Survey of the Pacific Coast*, p. 19.

[22]Dennis, *Analysis and Costs of Processing Strawberries for Freezing*, pp. 9–13.

[23]R. H. Reed, *Survey of the Pacific Coast*, pp. 17–21.

Table 8.1: **Pacific Frozen Strawberry Processing**

Characteristics	California	Oregon	Washington
Strawberry Pack Dates:	-	-	-
Average	May 1 to Oct. 15	June 5 to July 17	June 19 to July 26
Maximum	Apr. 1 to Nov. 31	May 26 to Aug. 4	June 1 to Sep. 8
Total Operating Days:	-	-	-
Average	120	41	31
Maximum	175	60	47
Total Hours/Plant:	-	-	-
Average	995	(not collected)	213
Maximum	2890	(not collected)	384
Total Output (1954)	50,800 tons	39,900 tons (combined)	

Table 8.2: **California Frozen Strawberry Processing**

	Input Capacity (lbs/hour), California Facilities		
Costs	5,000	10,000	20,000
Variable Costs:	-	-	-
Feedstock Intake	$3.82/hour	$5.72/hour	$9.54/hour
Sorting Equipment	$0.29/hour	$0.49/hour	$0.87/hour
Mixing Equipment	$0.21/hour	$0.23/hour	$0.47/hour
Sugar/Processing	$35.50/100 hours	$53.75/100 hours	$91.25/100 hours
Fixed Costs:	-	-	-
Feedstock Intake	$1,124/year	$1,485/year	$2,022/year
Sorting Equipment	$620/year	$980/year	$1,745/year
Mixing Equipment	$534/year	$617/year	$1,233/year
Sugar/Processing	$1,073/year	$1,650/year	$2,805/year

Sources: Reed, *Survey of the Pacific Coast*, 1957; Dennis, *Analysis of Costs of Processing Strawberries for Freezing*, 1958.

Figure 8.3: **California Plant Layout, 1950s**

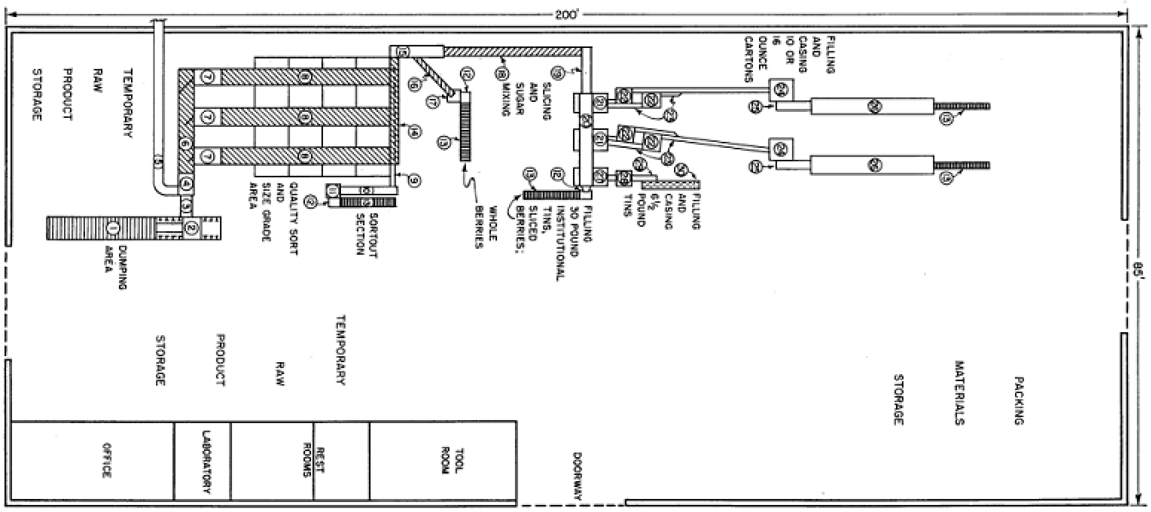
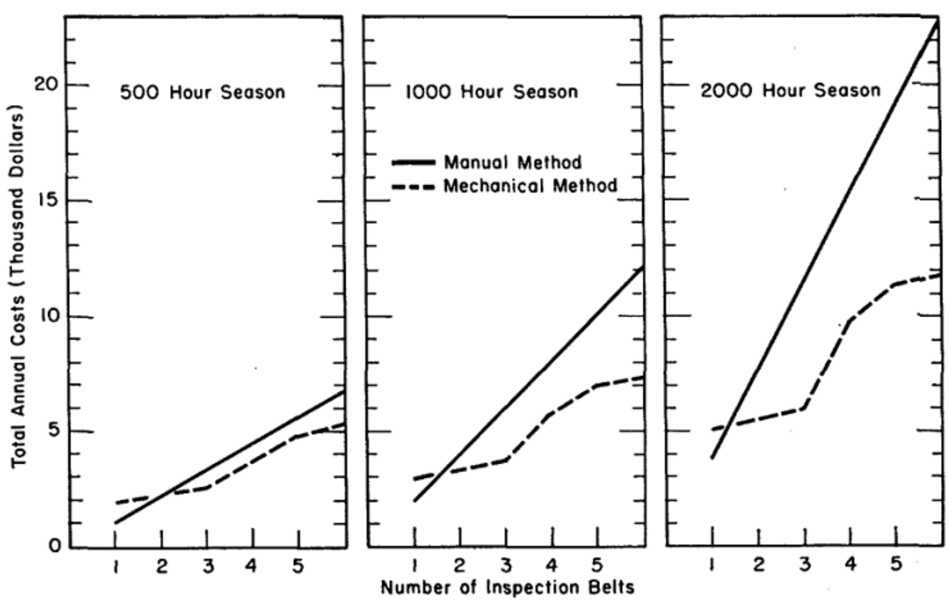


Fig. 17. Floor plan for a representative, medium-sized strawberry processing plant.

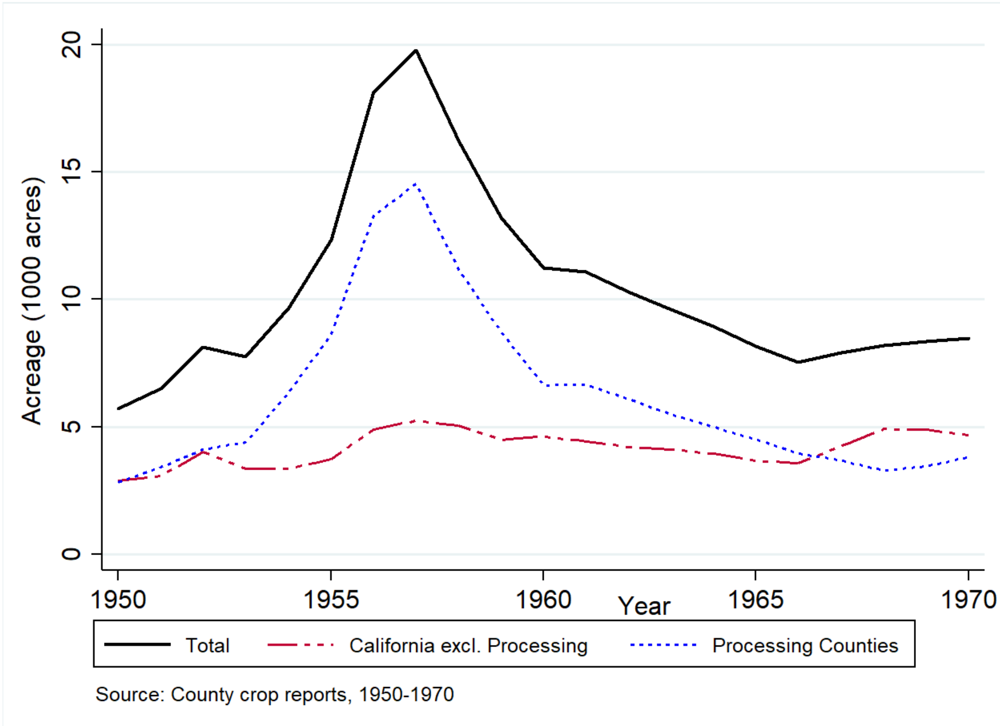
Source: Dennis and Sammet, *Interregional Competition*, 1961

Figure 8.4: **Capital Efficiency**



Source: Dennis and Reed, *Frozen Strawberries*, 1957

Figure 8.5: **Processing and Non-Processing Acreage, 1950-1970**



"Processing counties" are Monterey, San Joaquin, Santa Clara, Santa Cruz, and Stanislaus.

8.3 Speculation and Technological Change

The confluence of urbanization, varietal improvement, and a new, remunerative market would lead to an unprecedented level of growth in the strawberry industry, which expanded from 6000 acres in 1950 to almost 21,000 in 1957. Growth in production was thought to be driven by high prices in the frozen market and the comparative ease of entry given the lower quality standards for processed strawberries. Expansion followed a cycle of brief, relatively stable periods punctuated by bursts of prodigious growth, as we would expect given the lag time between cultivation and full production. Three quarters of new acreage was localized to Monterey County and its neighbors, which housed the majority of processing facilities in the state. Monterey, despite initially cultivating just 500 acres in 1950, brought an additional 6,300 under cultivation by 1957. Collectively, San Joaquin, Santa Clara, Santa Cruz, and Stanislaus underwent a similar expansion, from a combined total of 2,300 acres to 7,300 over the same period. Output rose dramatically; between 1943 and 1953, production of frozen strawberries increased from 1 million to 81 million pounds, and California would surpass Oregon as the largest supplier in the national market. In 1956, production would briefly peak at an unprecedented 150 million pounds, at which point California growers were responsible for just over half of all frozen strawberries in the country.[24]

[24]Bain and Hoos, *The California Strawberry Industry*, pp. 127–140.

Figure 8.6: **California Acreage, 1950-1970**

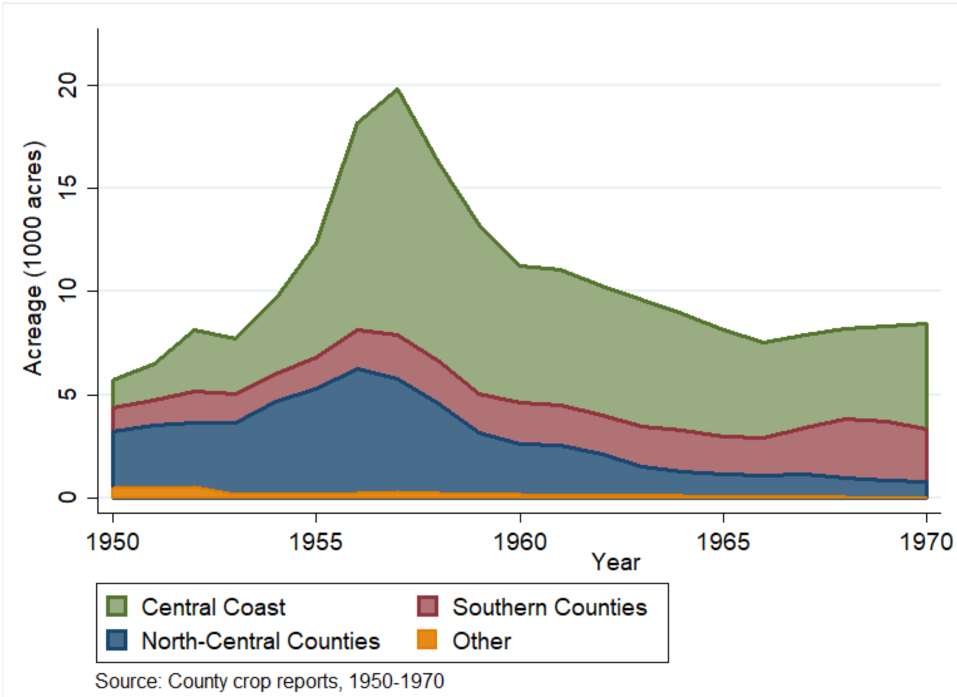
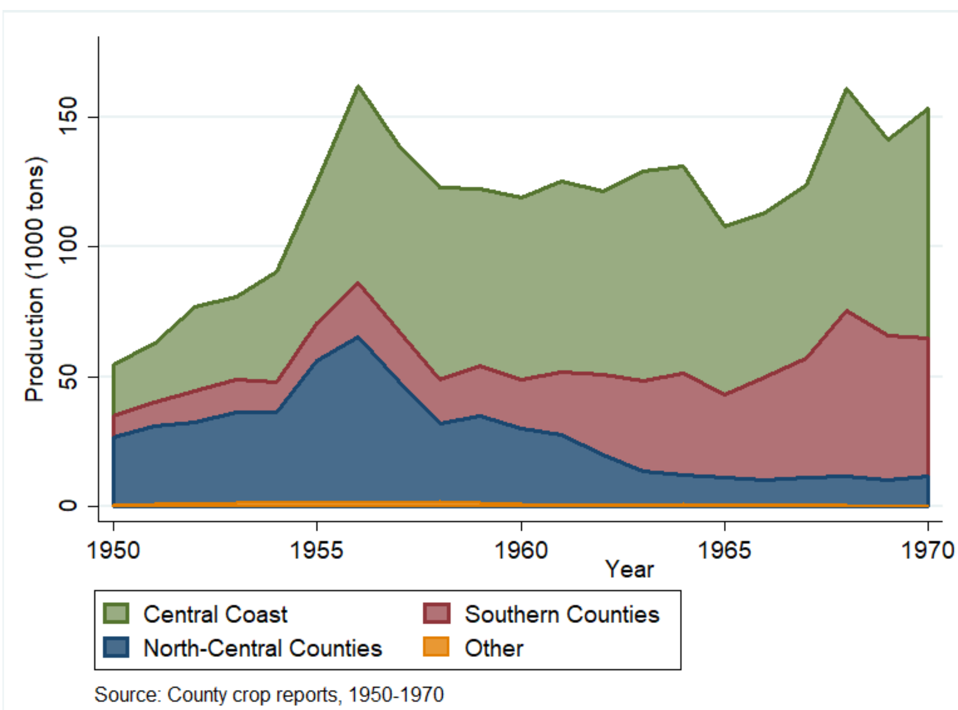


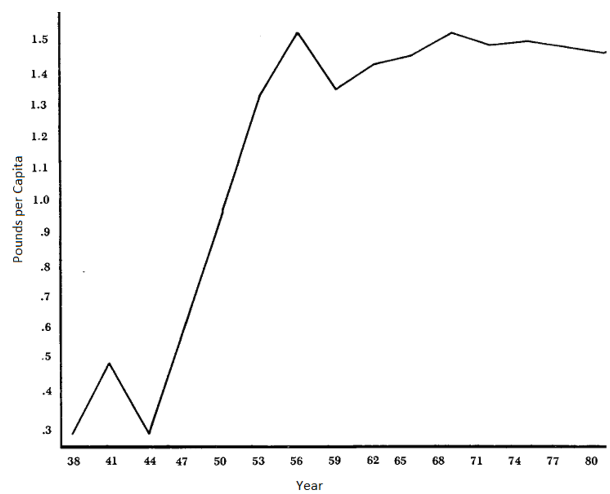
Figure 8.7: **California Production, 1950-1970**



Coastal: Monterey, San Benito, San Luis Obispo, Santa Barbara, Santa Cruz, Ventura; **North-Central:** Alameda, Fresno, Sacramento, San Joaquin, Santa Clara, Stanislaus; **Southern:** Imperial, LA, Orange, Riverside, San Bernardino, San Diego. *Not all county crop reports separated fresh and frozen production consistently, requiring aggregation.

The general trend of acreage and production is presented in Figures 8.7 and 8.8, and show that this period was extremely short-lived; following 1957 the strawberry industry would experience an acute "readjustment" in the processing market.[25] Consumption of frozen strawberries had leveled out in 1957, and in 1958 it would decline for the first time since WWII. This leveling-out coincided with an unusually high frozen pack; between 1955 and 1956, California production of frozen strawberries increased by 50 percent, translating to a 20 percent increase countrywide. This surplus and the resulting carryover into the next year caused processor prices to fall precipitously, from 17 cents per pound in 1955, to 14 in 1956, and to 10.5 in 1957. Depending on the district, this was anywhere from 5 to 25 percent below a grower's production costs, causing many to exit the market; frozen output soon returned to a stable 70 to 75 million pounds.[26] Bain and Hoos (1963) and Miriam Wells (1996) later argued that the industry's rapid expansion and contraction were both driven by speculation.[27] Nationally, frozen consumption had increased 50 percent between 1950 and 1956; this growth, pictured in Figure 8.8, kept processor prices consistently high and nearly equivalent to that of the fresh market. This attracted a large number of individuals to strawberry cultivation, many of whom had no agricultural background. Counties that had experienced particularly large increases in acreage also saw a decline in productivity; in particular, average yields in Monterey County decreased by almost 50 percent between 1950 and 1957. We would anticipate if increasingly marginal land or less experienced growers were entering production.[28] After prices fell, acreage in primary processing counties decreased by 50 percent or more; in contrast, acreage elsewhere in California was primarily oriented towards fresh market production, and, as seen earlier in Figure 8.5, would remain comparatively stable throughout the 1950s and 1960s.

Figure 8.8: **Frozen Consumption, 1938-1980**



Source: Padfield and Thaler, *The US Processed Strawberry Market*, 1980

Understanding the causes motivating readjustment is necessary to disentangle it from the ongoing reduction in acreage that persisted during the 1960s. Frozen market prices rebounded quickly; by 1966 they had reached 16 to 20 cents per pound, equal to or in excess of average processing prices during the 1950s. This trend ostensibly should have been reflected in cultivated acreage, but, referring again to Figure 8.5, it continued to to decline. Total yields, on the other hand, would gradually increase over the same period, as gains in productivity post-1960 more than compensated for the loss of acreage.

[25]Bain and Hoos, *The California Strawberry Industry*, p. 17.

[26]A. Reed, "A Prevue of California Agriculture", p. 1119.

[27]Wells, *Strawberry Fields: Politics, Class, and Work in California Agriculture*, pp. 33–34.

[28]Bain and Hoos, *The California Strawberry Industry*, pp. 18–31, 138–140.

8.4 The Impact of Methyl Bromide

The countervailing trends of acreage and production marked the beginning of the fumigation era of California strawberries and the intensification of the industry. According to Wilhelm and Paulus, MB/Pic fumigation had reached virtually 100 percent adoption on new strawberry acreage by 1965; while we will investigate the credibility of this claim in a later section, most literature suggests that the rate of adoption was exceedingly rapid.[29] Despite the fact strawberries' high value and limited acreage requirements partially insulated them from the effects of urbanization, they were still subject to competing pressures of soil-borne disease and a need to remain in close proximity to capital. To strawberry growers, the introduction of MB/Pic fumigation in 1960 simultaneously represented insurance, yield augmentation, and geographic stability; it would become the cornerstone of contemporary and future intensification, as innovation and capital investment were dependent on its use.

Both direct and indirect effects of fumigation were considerable. Depending on the county, yield per acre increased up to 100 percent by 1965, with the largest gains observed in counties where adoption occurred earliest. By 1969, state yield per acre had reached five times the national average.[30] The elimination of soil-borne pest pressure and the replant problem would end nomadic cultivation practices in favor of repeated cropping, with some farmers shifting practices within one to two years.[31] This offset some of the cost of fumigation by reducing expenditures on land preparation and weeding labor costs. Experiment Station risk analyses from 1961 and 1968 indicate strawberries had become more uniform in terms of both yield and economic outcomes. Variation in strawberry yield decreased from 9 percent to 5 percent, while variation in gross income fell from 13 percent to 4 percent - the lowest of the 35 major fruit and vegetable crops included in the study.[32,33]

Critically, fumigation also enabled a geographic redistribution of production, which can be observed in Figures 8.9 through 8.11. Acreage and production in 1950 are widely dispersed, with a majority of counties south of San Francisco engaged in at least some level of cultivation. In 1955, we are viewing the initial speculative buildup in Monterey County and its inland neighbors before it peaked in 1957; in 1960, we are observing its decline. While not pictured, acreage in Monterey County would triple between 1955 and 1957, then would fall by 50 percent between 1957 and 1960. After the introduction of MB/Pic, most counties exhibited a reduction in acreage, although this was unevenly distributed. With the exception of Fresno County, virtually all commercial cultivation of strawberries in the interior districts ceased within two decades of the introduction of fumigation. Coastal districts shed acreage until the late 1960s, but at a slower rate; their production also continued to increase during this period. Southern California - which, not coincidentally, saw the largest benefits from damage control - was the only region to bring additional acreage under cultivation.[34,35,36]

[29] S. Wilhelm and Paulus, "How Soil Fumigation Benefits the California Strawberry Industry", p. 268.

[30] Johnston and Dean, *California Crop Trends*, p. 90.

[31] S. Wilhelm and Paulus, "How Soil Fumigation Benefits the California Strawberry Industry", p. 268.

[32] H. Carter, Dean, and A. Reed, *Risk and Diversification for California Crops*, pp. 5–8.

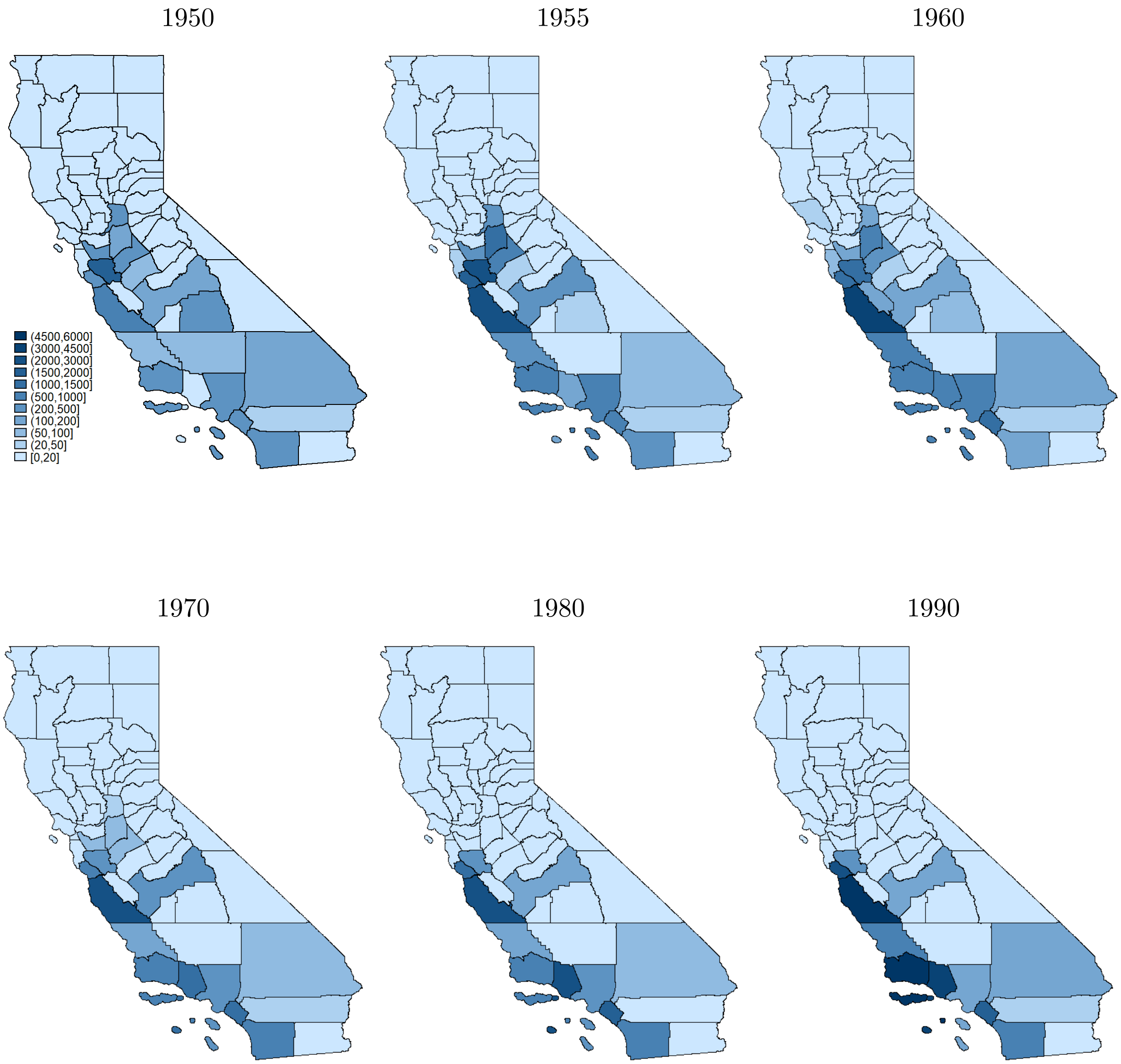
[33] H. Carter, Jensen, and Dean, *Risk and Diversification for California Crops (Revised)*, pp. 5–8.

[34] Thomas, *The Production of Strawberries in California*, pp. 9–13, 22–23.

[35] Bain and Hoos, *The California Strawberry Industry*, pp. 28–32.

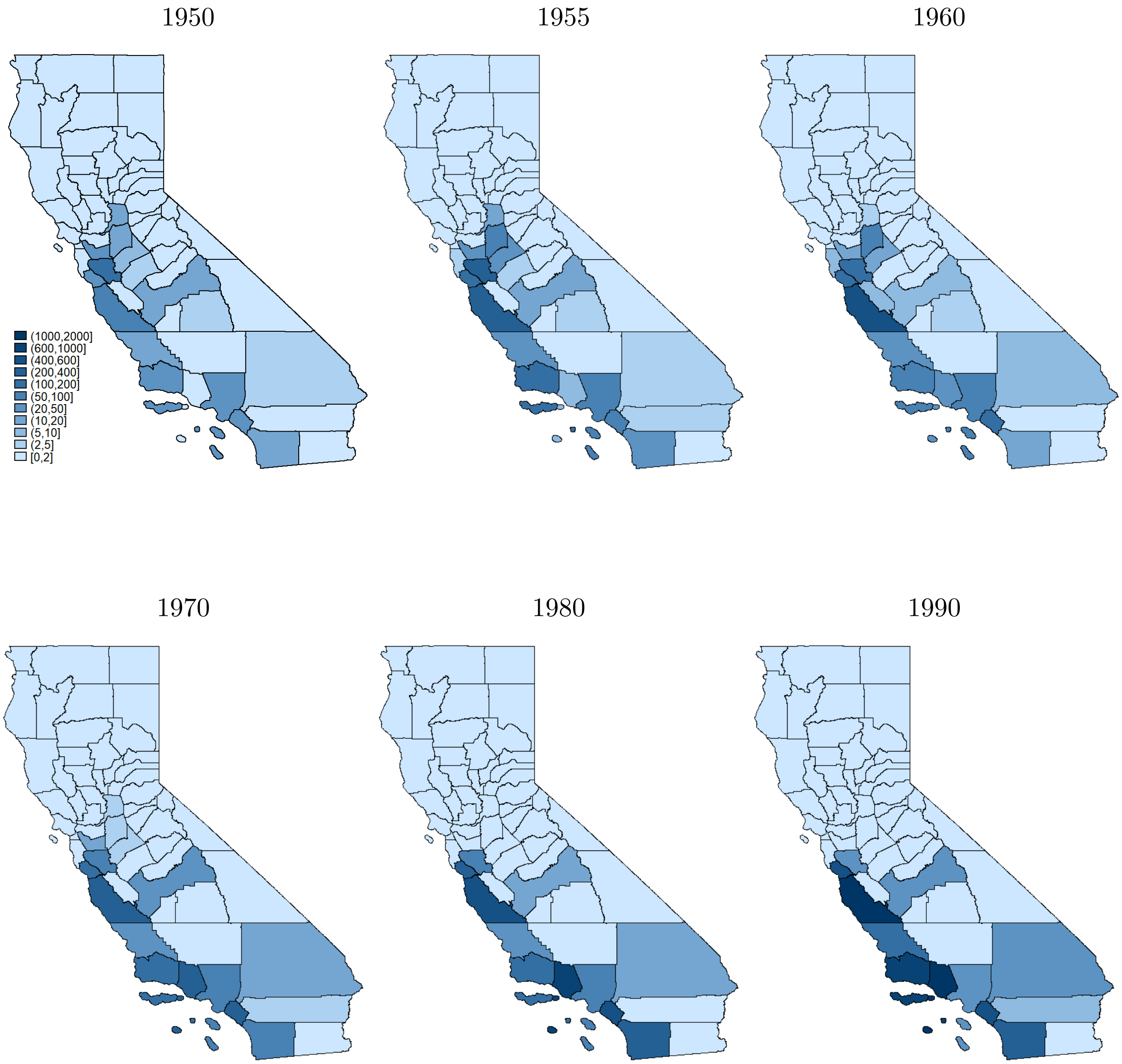
[36] Dennis, *The Location and Cost of Strawberry Production*, pp. 14–22.

Figure 8.9: **California Acreage, 1950-1990**



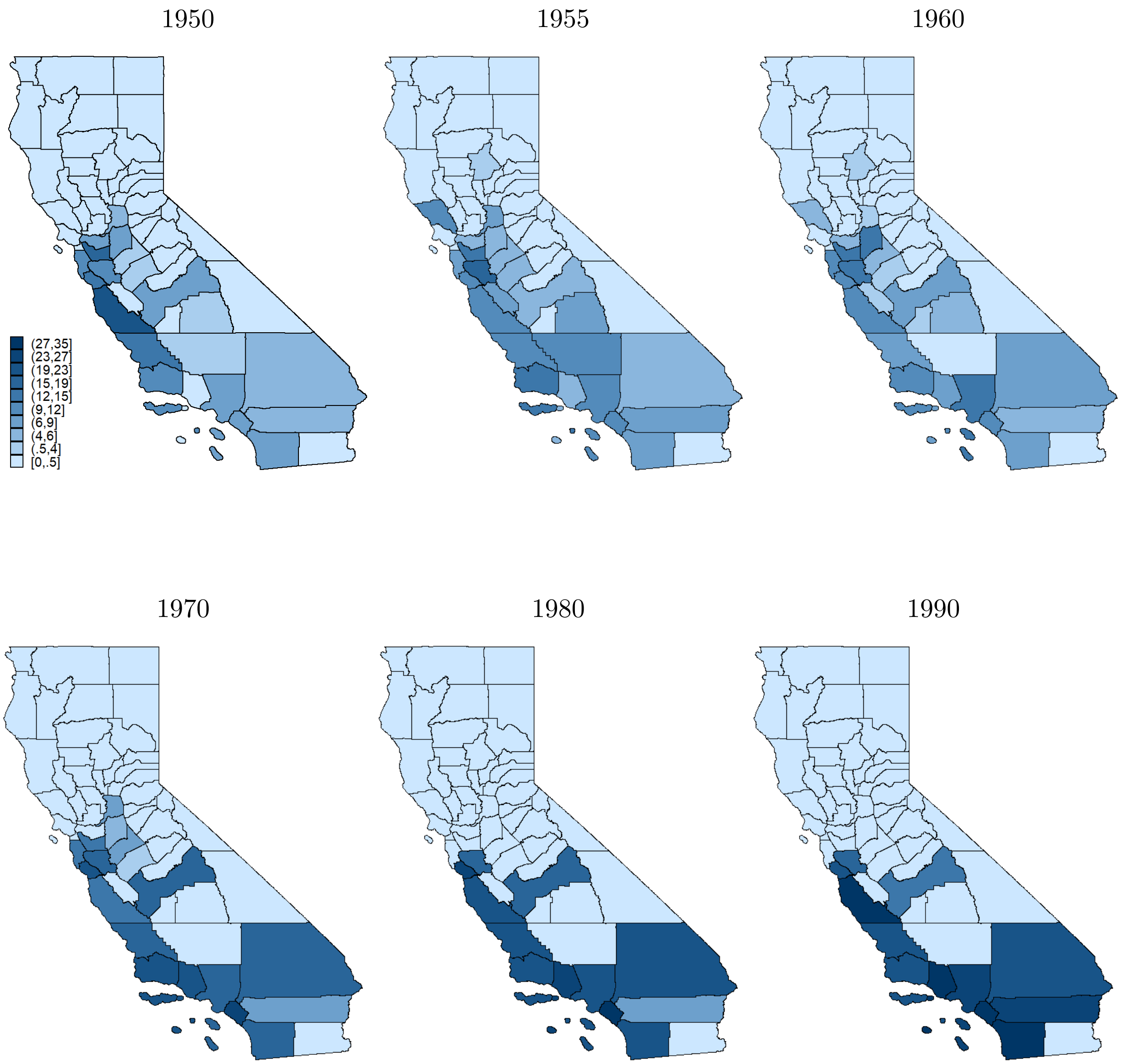
Source: California county crop reports, 1950-1990.
Ventura County reported production in 1950 but did not include acreage.

Figure 8.10: **California Production, 1950-1990**



Source: California county crop reports, 1950-1990. Value of production given in 100 tons.
*Note: Some production data were missing from crop reports in 1950 and 1955. Estimates were backed out by dividing the value of production by average price.

Figure 8.11: **California Yield per Acre, 1950-1990**



Source: California county crop reports, 1950-1990. Value given in tons/acre.
*Note: lower bound chosen to include all strawberry producers; counties in the 0.5 tons/acre category had no recorded production.
Acreage data was missing for Ventura County in 1950.

The preceding heatmaps are illustrative of both the scope and the magnitude of the post-fumigation industry reorientation. Outside of southern California, productivity would actually trend downward between 1950 and 1960 with the influx of speculative acreage. Monterey was particularly extreme; yield per acre would fall from 19 tons in 1950 to 4 tons in 1957. By 1970, the impact of fumigation adoption on yields is apparent, as is the widening gap in productivity between the interior districts and the coastal/southern ones. By 1980, strawberry cultivation had converged almost entirely to counties along the coast, and by 1990, productivity has become essentially homogeneous between remaining producers. Counties that exited production were not necessarily those with low initial yield per acre, but were primarily those that did not show increases in productivity post-1960, suggesting a connection to the non-adoption of fumigation.

Table 8.3: **Strawberry Production Budgets, 1959.**

Characteristics	Stanislaus	Monterey/Santa Cruz
Typical Acreage	15 acres	20 acres
Average Bed Life (Harvest Years)	2 years	3 years
Equipment Investment	$14,700 ($980/acre)	$19,300 ($965/acre)
Expected Yield (annual)	5 tons/acre	11.4 tons/acre

Costs		
Land Rent	$75/acre	$100/acre
Establishment Year:	-	-
Labor	$378/acre	$712/acre
Material	$230/acre	$457/acre
Misc.	$172/acre	$50/acre
Post-Establishment Year:	-	-
Labor	$209/acre	$309/acre
Material	$48/acre	$104/acre
Misc.	$14/acre	$6/acre
Annual Overhead, Taxes	$69/acre	$377/acre
Wage Rate	$1.00-$1.25/hour	$1.10-$1.35/hour
Non-Harvest Cost	$669/acre	$1,163/acre
Harvest Cost	$673/acre	$1,026/acre
Avg. Annual Cost	$1,342/acre	$2,189/acre
Avg. Production Cost	$0.134/lb	$0.096/lb

Non-harvest cost is a weighted average of establishment/non-establishment years based on planting lifetime.
Source: Dennis, *The Location and Cost of Strawberry Production*, 1959.

The economic conditions motivating the redistribution of acreage from the interior districts are illustrated in Table 8.3. This presents a comparison of the strawberry producing districts of Monterey/Santa Cruz and Stanislaus, proxies for the Central Coast and interior valleys, respectively. These budgets were compiled at the end of the 1950s and immediately preceded the introduction of MB/Pic fumigation. The annual cost of production in Monterey/Santa Cruz averages out to more than 50 percent above that of Stanislaus, yet per-unit costs of production are almost 30 percent lower due to the magnitude of difference between yields. This is despite the longer average bed life in Monterey/Santa Cruz, as fourth-year yields were roughly half the size of the second year.[37] Farmers in the Monterey/Santa Cruz region not only possessed a comparative advantage in production, but given the higher cost of establishment and wage rate for weeding labor, they would also derive greater value from the adoption of fumigation.

8.5 Post-Fumigation Innovation

Many aspects of production were indeed fundamentally altered by technological adoption. In *Wilted*, Julie Guthman instead emphasizes the role of technology adoption during the 1950s and 1960s in what she terms a "shakeout" of strawberry growers. These technologies were "developed and promulgated by institutions of repair"[38] and were specifically intended to mitigate structural disruptions to the strawberry industry; the advantages they conferred meant that growers that did not adopt them were eventually forced to exit production. Although Guthman conflates the effects of the frozen market crash and the more gradual consolidation of acreage in the 1960s, this is consistent with Willard Cochrane's model that non-adopters will leave an industry if technology increases adopter productivity, causing prices to decline.[39] Furthermore, previous research suggests that changes in the relative factor prices of capital and labor served as a "push" factor, causing workers to exit agriculture, while opportunities in urban centers were simultaneously acting as a "pull."[40]

Below, we will discuss some of the innovations that fumigation made economical for growers to adopt; in some cases, their successful implementation was entirely predicated on chemical damage control.

8.5.1 Planting Systems

Victor Voth, one of the most preeminent strawberry horticulturists of the University of California, would introduce two new planting systems in the 1950s. Known as "summer planting" and "winter planting," these systems accelerated plant development and increased yields through the manipulation of strawberry growing conditions - specifically, the cycles of growth and dormancy triggered by ambient temperatures. Like many plants, strawberries have what is known as a "chilling" requirement - a minimum amount of time spent at low temperatures (sub-7°C) to trigger a state of dormancy in the plant. Failure to meet chilling requirements disrupts this cycle and can cause reduced yields or irregularities in fruit setting. Summer planting was first promulgated in 1955, and circumvented the seasonal aspect of chilling by artificially inducing it with the use of refrigeration. Nursery plants, dug out

[37] Hendrickson, *Strawberry Culture in California*, p. 5.

[38] Guthman, *Wilted*, p. 160.

[39] Cochrane, *The Development of American Agriculture: A Historical Analysis*.

[40] Kislev and Peterson, "Prices, Technology, and Farm Size".

in early winter, were stored for 8 to 9 months at below-freezing temperatures to satisfy their chilling requirements by the time they were planted in mid to late summer. Summer planted strawberries would enter full production the following spring - effectively cutting the time to their first harvest by half a year - and would produce particularly heavy yields over an extended period. The winter planting system was formally introduced in 1958, though the concept had been used in commercial production to some extent since the early 1940s. Nursery transplants that had received sufficient chilling hours were dug as early as November and then immediately set in districts with comparatively warm winters - the coastal climates of central and southern California - where they would produce a particularly large early crop and then continue fruiting at a reduced level a number of months. This schedule also made accumulation of chilling hours feasible without artificial refrigeration, provided that the strawberries were propagated at high elevation; over time, nurseries would migrate from the Sacramento Valley to mountainous areas in northern California to satisfy this demand.[41,42 43]

Summer and winter planting were generally used in tandem throughout most of California: a rotation between summer and winter planting allowed sufficient time to prepare the soil between each strawberry crop, and a mixed schedule was a method to spread risk out over the season. There were, however, a few notable differences between the two systems. Relative to summer planting, winter planting sacrificed a portion of total yield and season length in exchange for particularly high-quality berries and a shorter interval between planting and first harvest. Winter planting tended to align peak yields with peak annual prices, although summer plantings often continued long enough to benefit from a price bump from diminishing supply later in the year. Total income was higher under summer planting, although longer harvests meant costs of labor and irrigation were higher as well; winter plantings required less weeding, pruning, and general maintenance as the crops were removed after just a few months. There was also some heterogeneity in how strawberry varieties performed under each system, which played a significant role in which of the two predominated. The Lassen, for example, was well-suited for summer planting, while strawberries introduced in the 1960s - Tufts and Tioga - performed well under either schedule. In the late 1980s, the Douglas strawberry catalyzed a major shift in southern California in favor of winter planting, under which the Douglas performed exceptionally well.[44,45,46,47,48]

Provided they had received enough chilling and were cultivated under appropriate conditions, first-year strawberries were immensely productive under these systems, and after 1960 existing perennial culture was gradually replaced with annual planting schedules. This transition occurred more rapidly in southern districts in large part because it was not a major adjustment - the age distribution of strawberry vines was already heavily skewed towards younger plantings. In the years leading up to fumigation, half to two-thirds of southern

[41] Voth and Bringhurst, "Culture and Physiological Manipulation of California Strawberries", pp. 889–890.

[42] Voth, *The California Strawberry Industry - 1985*, p. 136.

[43] S. Wilhelm and James Sagen, *A History of the Strawberry*, pp. 225–227.

[44] Voth and Bringhurst, "Culture and Physiological Manipulation of California Strawberries", pp. 889–890.

[45] S. Wilhelm and James Sagen, *A History of the Strawberry*, pp. 225–226.

[46] Bringhurst, Voth, and Hook, "Relationship of Root Starch Content and Chilling History to Performance of California Strawberries", pp. 373–375.

[47] Darrow, *The Strawberry*, pp. 231–235.

[48] Wells, *Strawberry Fields: Politics, Class, and Work in California Agriculture*, pp. 160–165, 180–184.

acreage was replanted annually, and 90 percent was renewed within two years; in contrast, two-thirds of the acreage outside of southern California was at least three years of age. This is attributed to southern growers' higher resource endowments and tighter land constraints, as annual planting was necessarily more resource-intensive than perennial culture with significantly larger outlay on land preparation and nursery expenses. The abbreviated lifetime of a strawberry bed meant it was no longer possible for growers to defray material and labor costs by allowing runners to set; instead, they began to "plant fields solid,"[49] relying entirely upon nursery propagated transplants. In return, growers' yields were substantially larger, and the removal of the strawberries at the end of the season also mitigated some of the pest damage associated with multi-year crops.[50,51,52,53,54]

8.5.2 Plasticulture and Drip Irrigation

In conjunction with fumigation, a strawberry "plasticulture" would emerge towards the end of the 1950s. Plasticulture - the use of polyethylene films as a form of "mulch" - was used to manipulate soil temperature to induce greater productivity. After a strawberry bed has been set with plants, they are covered in tightly-stretched sheets of plastic, with the plants pulled through holes punched into the sheeting. As with organic mulch, the plastic acts as a barrier between the fruit and the soil, conserving moisture and reducing the likelihood of fruit damage via fungal colonization. The key difference, however, is that polyethylene mulch raises the temperature of strawberry beds anywhere from 2 to 7°C depending on the time of the year. Warmer soil is critical for larger winter-planted strawberry yields as it promotes early fruit production and active plant growth, and allows for earlier planting than might otherwise be possible given prevailing temperatures; it is particularly important if the season is colder than average. Mulch application experiments generated substantial yield responses, ranging anywhere from 30 to 50 percent over that of non-mulched fields.[55]

Drip irrigation systems were another plastic-intensive innovation, and were readily adopted by strawberry growers. Imported from Israel to California in the late 1960s, drip systems were originally used in avocado and grape production. After the introduction of drip tape, they were adopted by strawberry growers, and by 1976 drip used to irrigate over a quarter of all strawberry acreage. By 1986, this figure had surpassed 95 percent, and the technology has since been modified to deliver both fertilizer and pesticides.[56] In comparison, the adoption rate in 1988 was just 5 percent across all irrigated acreage in California. Drip irrigation is comprised of plastic tubing embedded with a series of emitters, which are used to maintain a slow, precise application of water at a uniform rate throughout the entire strawberry bed. Drip irrigation is more capital intensive than traditional furrow irrigation, as pumps and filters are necessary to provide sufficient pressure to distribute the water and

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[49] S. Wilhelm and James Sagen, *A History of the Strawberry*, pp. 225–226.

[50] Cyclamen mites, for example, will inflict serious losses on strawberry crops in their second year, as they will overwinter in the crowns of the plants before emerging the following summer.

[51] University of California Statewide Integrated Pest Management Program, *Cyclamen Mite*.

[52] Voth and Bringhurst, "Culture and Physiological Manipulation of California Strawberries", pp. 889–890.

[53] Wells, *Strawberry Fields: Politics, Class, and Work in California Agriculture*, pp. 181–186.

[54] Thomas, *The Production of Strawberries in California*, pp. 38–39.

[55] Voth and Bringhurst, "Culture and Physiological Manipulation of California Strawberries", pp. 890–891.

[56] R. Taylor and Zilberman, "The Diffusion of Process Innovation: The Case of Drip Irrigation in California".

prevent clogs within the tubing. Once attached to this delivery system, the plastic tubing is run underneath the soil before the bed is covered by polyethylene mulch. The drip tubing is not permanent, and must be replaced regularly; even with filters, emitters are occluded over time by salt or other debris.[57,58]

Drip systems enable more precise irrigation, increasing the *effective* application of water - the proportion that is actually absorbed by the plant - reducing water usage by more than half in USDA Field Station strawberry trials. In addition, irrigation water typically contains dissolved salts, which build up in the soil over repeated applications; these salts must be pushed below a crop's root zone by additional water, known as the "leaching fraction." By reducing the total amount of applied water, drip systems reduce the rate of soil salinization, and in Field Station trials this was accompanied by a corresponding 10 percent increase in yield and fruit size compared to furrow irrigation. Other, less immediately-quantifiable benefits of drip systems include a reduction in weed populations, facilitating picking by keeping access paths dry, and preventing fungal contamination caused by fruit coming into contact with water. Drip irrigation also circumvented or relaxed a number of physical constraints. Bed width, for example, was no longer restricted by lateral percolation of water in the furrow, and in the 1980s and 1990s growers began to enlarge them to accommodate increased planting density. Yield per acre increased in proportion to the additional plant population, allowing growers to consolidate their operation onto less acreage and decrease costs. Other constraints, such as land grade or soil water-holding capacity, were of diminished importance given the more precise application of water.[59,60,61,62,63]

8.5.3 Strawberry Breeding

Strawberry breeding was fundamentally changed by the success of the UC program. In a sphere that had been predominantly occupied by the trial-and-error results of individuals, the UC program represented the entry of institutions, with the associated concentration of human capital and more scientifically formal approach to cultivar development. Computer technology held significant promise for easing the data burden of large scale trials and improving the interpretation of their results.[64] In 1952, after the end of a 7-year lull in funding following the introduction of the University varieties, the program would again resume pomological research in its full capacity. They were joined by Driscoll Strawberry Associates, later Driscoll Inc., who would develop their own proprietary varieties with the expertise of Thomas and Goldsmith, who by that time had resigned from the breeding program and founded the non-profit Strawberry Institute of California. Nurseries and individual breeders continued to make their own contributions to the field, often in collaboration with these

[57]Wells, *Strawberry Fields: Politics, Class, and Work in California Agriculture*, p. 185.

[58]R. Taylor and Zilberman, "The Diffusion of Process Innovation: The Case of Drip Irrigation in California", pp. 2–4.

[59]Voth, *The California Strawberry Industry - 1985*, pp. 136–137.

[60]Voth, "Ten Years of Drip Irrigation", pp. 90–92, 95–96.

[61]Hanson and Bendixen, "Drip Irrigation Evaluated in Santa Maria Valley Strawberries", pp. 1–3.

[62]Caswell, Zilberman, and G. E. Goldman, "Economic Implications of Drip Irrigation", p. 4.

[63]Welch, Greathead, and Beutel, *Strawberry Production and Costs in the Central Coast of California*, p. 2.

[64]Darrow, *The Strawberry*, pp. 229–230.

larger institutions.[65] Together, these groups facilitated California's pivot towards the national strawberry market, developing cultivars that were "larger, more attractive, firmer, better flavored, [and] easier to harvest."[66]

In 1980, Bringhurst and Voth announced the development of the first "day-neutral" cultivars.[67] This innovation was the result of several decades worth of research into plant photoperiodism - the physiological changes that a plant undergoes in response to changes in day length. It became a key selection criteria for cultivars following research into strawberry-specific photoperiodism in the 1950 and 1960s as it governs how and when the plant will set fruit.[68,69] California strawberries up until this point were all categorized as "summer fruiting" or "June-bearing" varieties, with variation in whether they were early, mid, or late-season bearers. These types of strawberries are now more generally referred to as "short-day" varieties, as they create flowers in the short days of spring and fall.[70] Short-day production tends to be bimodal, with a heavy crop in the spring that subsides over the summer, typically ending with a moderately large harvest in the fall. In contrast, day-neutral plants are less affected by changing day length, and will instead continually produce flowers and fruit as long as they stay above a certain temperature. Although short-day cultivars produced higher-quality berries - at least at this juncture - day-neutral yields were larger in aggregate, and occurred at a more uniform rate across a longer season.[71,72]

8.6 The Role of Methyl Bromide

Despite the fact that chloropicrin was both able to control the replant problem and served as the primary fungicidal agent in the MB/Pic mixture, chloropicrin fumigation by itself did not have the same transformative effect on the strawberry industry. One possible explanation is that it was simply a quirk of timing; chloropicrin may have been in the early stages of adoption when MB/Pic was introduced. However, judging by chloropicrin's absence in crop budgets prior 1960, as well as the post-1960 yield patterns, this reasoning alone is not entirely satisfying. Instead, it suggests that the rate of MB/Pic adoption and subsequent transformation of the industry were more heavily predicated on the agricultural and economic benefits provided by the inclusion of methyl bromide. Given the cost of fumigation, one particularly valuable advantage of MB/Pic was risk reduction; a major deficiency of chloropicrin as a solo fumigant is its poor soil diffusion, which can potentially leave gaps in the physical coverage of treatment. Methyl bromide, in addition to enhancing overall pest control, diffuses readily and acts as a carrier for chloropicrin, ensuring better soil distribution and consistency. This also mitigates any errors made while fumigating. Another advantage of MB/Pic relative to chloropicrin was that chemical weed control allowed growers to sub-

[65] The multifaceted relationships between these actors are examined in detail by Herbert Baum in *The Quest for the Perfect Strawberry*.

[66] Darrow, *The Strawberry*, p. 228.

[67] Bringhurst and Voth, "Six New Strawberry Varieties Released", pp. 12–13.

[68] Guttridge, "Further Evidence for a Growth-Promoting and Flower-Inhibiting Hormone in Strawberry", pp. 612–613, 619.

[69] Ahmadi, Bringhurst, and Voth, "Modes of Inheritance of Photoperiodism in *Fragaria*", pp. 146–147.

[70] Darrow, *The Strawberry*, p. 392.

[71] Bringhurst, Voth, and Shaw, "University of California Strawberry Breeding", p. 999.

[72] Wells, *Strawberry Fields: Politics, Class, and Work in California Agriculture*, p. 184.

stitute fumigation for labor expenditures. Monterey/Santa Cruz crop budgets from 1959 and 1969 indicate more than a 50 percent reduction of labor-hours devoted to weeding in the first production year; this amounted to roughly $130 per acre, over a third of the cost of fumigation. Methyl bromide's herbicidal properties were also critical for the adoption of plasticulture, as the yield response from warming the soil is best achieved through the use of clear material; opacity impedes transmission of solar radiation. Darker colors of plastic can be actively detrimental for strawberries, as they are capable of absorbing enough heat to cause contact burns on low-hanging fruit.[73] However, weeds also respond positively to increased soil temperature; as clear plastic does not prevent them from receiving sunlight, they begin to compete with strawberries for resources. After the mulch was set, however, it was no longer feasible to remove weeds by hand; herbicidal fumigation became necessary to prevent them from germinating.[74]

Compared to plasticulture, other innovations in strawberry production were not as directly linked to methyl bromide's herbicidal properties, but their adoption was still dependent on the broad spectrum damage control offered by MB/Pic. Strawberry breeding priorities post-1960 were shaped by fumigation, which enabled growers to preferentially adopt strawberries with superior market characteristics rather than disease resistance; these traits' importance had only been magnified by the shift towards nationally-marketed production. This trend can be seen in the prominent University-bred cultivars between the 1960s and the 1990s, virtually all of which were moderately or highly susceptible to verticillium wilt; this included Tufts, Tioga, Aiko, Douglas, Pajaro, and Camarosa, which were at different times the most widely cultivated strawberries in California. More resistant cultivars, like the aptly named "Wiltguard," were also introduced during this period, but never achieved significant commercial presence.[75,76,77,78] The success of winter and summer planting also depended upon highly effective pest control. Not only is verticillium wilt is more threatening to younger, less well-established plants, the adoption of these systems increased agricultural traffic between fruit production districts and northern counties' high-elevation nurseries.[79] This made provision of clean planting stock - transplants free from nematodes, viruses, or other pests - essential to reduce the possibility of cross-site contamination. Nurseries adopted a multi-layered approach to prevent the introduction of pests into the nursery as well as to keep the nursery transplants themselves from becoming a source of infestation for growers. The former relied on physical inspection, geographic isolation, and plant indexing - a method of detecting viral infection - to ensure strawberry runners were clean prior to propagation, while the latter depended heavily upon fumigation to guarantee transplants met phytosanitation standards.[80]

Drip irrigation is not materially dependent on fumigation, although it benefits from weed control and is virtually always paired with plastic mulch for additional soil moisture retention.

[73] Voth and Bringhurst, "Culture and Physiological Manipulation of California Strawberries", pp. 890–891.

[74] Voth, *The California Strawberry Industry - 1985*, p. 136.

[75] Bringhurst and Voth, "Six New Strawberry Varieties Released", p. 13.

[76] Baum, "Quest for the Perfect Strawberry", pp. 15–17.

[77] University of California Statewide Integrated Pest Management Program, *Characteristics of Public Strawberry Cultivars Commonly Grown in California*.

[78] Darrow, *The Strawberry*, p. 228.

[79] Bell, "Verticillium Wilt", p. 99.

[80] Darrow, *The Strawberry*, pp. 221–234, 287.

Even so, it is unlikely that drip irrigation would have been similarly embraced by growers had fumigation not controlled both verticillium wilt and the replant problem. Compared to furrow irrigation, drip systems require additional upfront investment in filtration, and the tubing must be replaced over time as its performance degrades. In an early report to the Strawberry Advisory Board, Voth noted that despite the impact on yield, water efficiency, and salt accumulation, drip systems were "prohibitively expensive"[81] compared to existing furrow irrigation and must be implemented judiciously by growers.[82] More recently, Taylor and Zilberman's (2017) case study of drip irrigation shows that, until the drought crisis of the late 1980s, adoption was limited to high-value, water-intensive crops - e.g., strawberries, as well as avocados and fresh-market tomatoes - in districts with expensive or more saline water.[83] However, these crops make poor rotation candidates for strawberries as they are also susceptible to wilt. Strawberry growers choosing to install drip irrigation on non-fumigated land would be forced to rotate with crops that would have otherwise not have justified the outlay of capital, which - as suggested by the threshold model discussed by Taylor and Zilberman - would necessarily lower adoption rates.

8.7 Adoption Patterns of MB/Pic Fumigation

Wilhelm and Paulus' claim about the adoption rate of MB/Pic is not entirely supported by other literature; Waldo, Bringhurst, and Voth (1969) imply that, while fumigation was indeed widespread, counties on the Central Coast had not yet reached full adoption.[84] Data from California's Department of Pesticide Regulation unfortunately only extends back to 1970, which prevents us from tracking the actual figures; however, it is possible to create a rough outline of the pattern of adoption using other sources. Strawberry crop budgets from the University of California indicate growers in southern districts were the first adopters of MB/Pic fumigation, likely followed by those on the Central Coast. Based on the aforementioned report by Waldo et al., fumigation may have reached full adoption earlier in the central valleys than on the coast, but data from county crop reports provide no evidence of a yield effect until the late 1960s. Of the six crop budgets compiled from 1955 to 1960, the counties of Stanislaus, Monterey, Santa Cruz, and Riverside recorded fumigation expenditures on either ethylene dibromide or an unlisted chemical at a similar cost of approximately $30 to $50 per acre. Orange and Los Angeles County budgets instead indicate methyl bromide and chloropicrin had already entered into production practices, although Orange County applied them as separate treatments instead of an MB/Pic mixture.[85] Between 1960 and 1962, MB/Pic treatments were also recorded in Santa Barbara and San Luis Obispo,[86] and appear for the first time in Riverside; in contrast, Monterey and Santa Cruz continued fumigating with ethylene dibromide. This pattern is seen in regional yields presented in Figure 8.12.

It is apparent that these three regions exhibit vastly different yield trends post-fumigation:

[81] Voth and Bringhurst, *Evaluation of an Experimental Bed-Top Irrigation System.*

[82] Voth and Bringhurst, *Drip Irrigation on Summer Plantings.*

[83] R. Taylor and Zilberman, "The Diffusion of Process Innovation: The Case of Drip Irrigation in California", pp. 9–15.

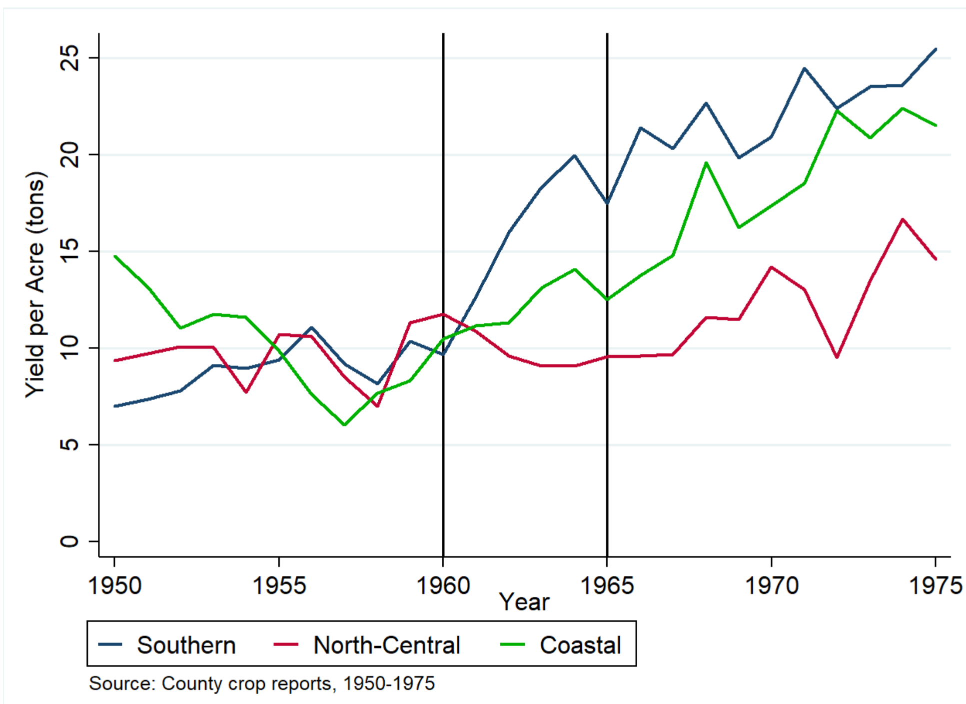
[84] G. Waldo, Bringhurst, and Voth, *Commercial Strawberry Growing in the Pacific Coast States*, pp. 3–5.

[85] S. Wilhelm, Paulus, and McCain, *Bringing Our Knowledge Up to Date on Soil Fumigation.*

[86] While the UC Davis archive lists the San Luis Obispo/Santa Barbara budget as 1958-1959, it was recorded in 1960.

an annual 20 to 25 percent growth rate in the south, a much shallower increase on the coast, and virtually zero change in the central counties. This pattern is consistent with the *threshold model*, an economic theory regarding innovation adoption and diffusion. In its simplest form, the threshold model assumes a set of heterogeneous, profit-maximizing producers are distributed unimodally over some characteristic which determines the profitability of technology adoption. At a given point in time, farmers above a critical threshold of this characteristic will choose to adopt, and those below the threshold will continue to use the traditional technology. Diffusion of the innovation increases as this threshold value falls over time, which occurs as the cost of the technology decreases and/or the profit differential between the traditional and the new technology widens.[87] In the case of strawberries, methyl bromide adoption was affected by regional heterogeneity; in particular, growers in southern California were better poised to derive value from fumigation, with higher market prices, tighter land constraints, and more frequent replanting all increasing potential gain from the technology.

Figure 8.12: **Yield per Acre by Sub-region, 1950-1975**



8.7.1 Logistic Growth Model

Zvi Griliches' (1957) observations on hybrid corn led him to suggest the logistic growth function as a potential model for its diffusion, simplifying the comparison of adoption between different states and crop reporting districts.[88] Given the trend of the yield data - specifically that of the southern region - this seems to be an appropriate model to represent the introduction of MB/Pic fumigation. Yield per acre serves as a proxy variable to compensate

[87]The threshold model is covered at length in Sunding and Zilberman (2001)

[88]Griliches, "Hybrid Corn", pp. 502–504.

for the lack of information regarding adoption; Wilhelm and Sagen's estimated five to six-year window of diffusion allows us to reasonably exclude the effects of other yield-enhancing innovations from this period. New varieties introduced around this time were either less productive than the Lassen - such as the Fresno, Torrey, and Solana - or were not released for cultivation until end of the window, e.g., the Tioga in 1964.[89,90] Summer planting had been introduced in 1955, and the adoption of annual planting, while not universal, was already practiced on roughly half of southern acreage.[91] Southern districts' emphasis on early fresh market production also mitigates the possibility that price might affect observed yield per acre via incomplete harvesting. Although the adoption of plasticulture was a significant contributor to yield, it was also inextricably linked to the use of methyl bromide.

We use the following logistic model:

$$Y = \frac{\alpha}{1 + e^{-(\beta + \gamma t)}} \tag{8.1}$$

where Y is the yield per acre, β and γ shape parameters of the function, t an index of time, and α a theoretical maximum yield approached asymptotically; this value arguably exists over limited time horizons as existing innovations are optimized and before new ones are introduced. We first examine how this model fits to the southern districts in aggregate, then individually to Los Angeles, Orange, San Bernardino, and San Diego County; Imperial County did not record strawberry production during this period, and Riverside cultivated less than 40 acres. Yields were strongly affected by the 1965 termination of the Bracero program, which resulted in acute labor shortages and an estimated single-year loss of 25 million pounds of strawberries. To adjust for this, an average of adjacent years was substituted.[92]

Table 8.4: **Southern Counties, Logistic Growth Model**

	Southern CA 1960-1965	Los Angeles 1960-1965	Orange 1960-1965	San Bernardino 1961-1967	San Diego 1962-1968
α	22.09***	19.09***	25.38***	17.33***	18.17***
	(0.396)	(0.497)	(2.975)	(1.240)	(1.354)
β	-0.274***	0.533***	-0.556***	-0.429**	-0.405**
	(0.036)	(0.065)	(0.453)	(0.124)	(0.125)
γ	0.612***	0.445***	0.699***	0.496***	0.509**
	(0.037)	(0.056)	(0.047)	(0.104)	(0.117)
N	6	6	6	7	7
Adj. R^2	.999	.999	.999	.998	.997

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Given this choice of proxy for adoption, the fit between data and model and the highly significant parameter values for all four regressions is encouraging. Graphically, it is apparent

[89] Bringhurst and Voth, "Summer-Planted Solana Berries", p. 6.

[90] Bringhurst and Voth, "Fresno, Torrey, and Wiltguard: New Strawberry Varieties for California Growing Areas", p. 12.

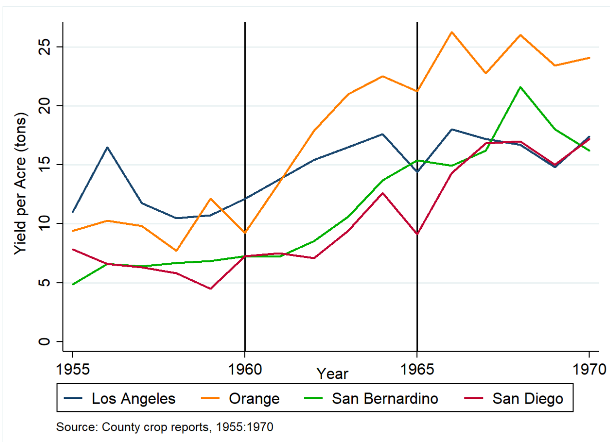
[91] California Crop and Livestock Reporting Service, *Strawberries, Acreage and Indicated Production.*

[92] Johnston and Dean, *California Crop Trends*, pp. 90–91.

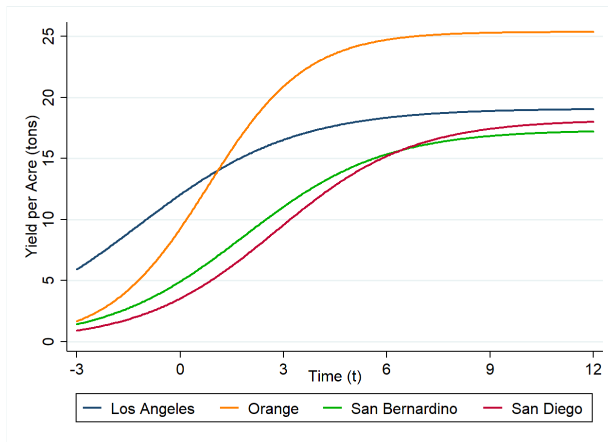
that Orange County derived particular benefit from fumigation, with higher maximum yields and a much faster rate of growth than either Los Angeles or San Diego. The positive value of β for Los Angeles suggests substantially faster initial adoption but a much lower "ceiling" - this is despite having similar pre-fumigation productivity to Orange County. In contrast, while San Diego and San Bernardino leveled out at similar maximums, they also possessed perceptibly lower initial yields. This is visually represented below in Figure 8.13:

Figure 8.13: **Model of Southern Yields per Acre**

(a) Southern Productivity



(b) Model



t=0 corresponds to 1960.

The cause(s) of the widening yield gap seen in Figure 8.13(a) is unclear, but there are a few potential explanations. One possibility is that disease pressure was simply much greater in Orange County, and therefore damage control had a much greater effect. Another possibility is that fumigation led to a quality-based reallocation of land in Orange County, which could extend to climate, water, or soil characteristics. In the latter case, soil composition maps from early surveys are suggestive of a discrepancy between the counties' suitability for strawberry production; many fertile soil regions in Los Angeles were also comparatively alkaline, which lowers yields in the case of strawberries.[93,94] This line of reasoning supported by the higher land rent in Orange County ($150) compared to Los Angeles ($50). Cost studies indicate that production in Los Angeles County was roughly 15 percent more expensive than Orange County - $5950 to $5200 - much of which came from higher irrigation costs.[95,96] Unfortunately, future Los Angeles cost studies were merged with Orange County, limiting their value post-1960.[97] Using Ag Census data, however, we observe a growing disparity in farm size between the two districts; the average strawberry farm in Los Angeles County expanded from 7.5 acres to 10.5 between 1959 and 1969, compared to a respective 9.5 and

[93]Eckmann, L. Holmes, and Guernsey, *Soil Survey of the Anaheim Area, California.*

[94]Mesmer, *Soil Survey of the Los Angeles Area, California.*

[95]Not Available, *Strawberry Cost of Production Study: Los Angeles County.*

[96]Not Available, *Strawberry Cost of Production Study: Orange County.*

[97]Francis and Rock, *Summer-Planted Strawberries Sample Production Costs: Orange-Los Angeles Counties.*

17.5 acres in Orange County.[98, 99]

With regards to San Bernardino and San Diego, the 1 and 2-year delays in productivity growth imply growers lagged slightly behind Los Angeles and Orange County in fumigation adoption. For San Diego, the eventual leveling off from 1967-1970 may suggest the adoption claim made by Wilhelm and Paulus was not universal, although this could also be evidence of slower recovery from the labor shortage.[100] San Bernardino and San Diego strawberry farms were on average somewhat smaller than Los Angeles and Orange County - slightly less than 7 and 5 acres respectively in 1959. A delay in adoption is therefore consistent with what we would expect based on economic theory: Just and Zilberman (1983) show that propensity to adopt a risk-reducing technology - such as fumigation - increases with the size of the farm.[101] Returning to the threshold model, the critical value governing adoption is expected decline over time; in this case, we would anticipate fumigators to refine their practices, reductions in the cost of chemical production, and the proliferation of fumigation-related services. In 1961, for example, the fumigation company TriCal was founded and a patent was issued for a new and less expensive method of chloropicrin manufacturing.[102] We note that between 1964 and 1969, average strawberry farm size in San Diego expanded from 5 to 32 acres, while total acreage increased from 118 to 520; this is supportive of a somewhat delayed adoption of methyl bromide. In contrast, however, cultivation in San Bernardino would only expand from 46 to 110 acres over the same period, and farm size would remain unchanged.[103] As productivity in both districts was nearly equivalent, this divergence must result from other factors; cost, location, seasonal timing, or some combination. Another possible cause is the 1960 completion of a major aqueduct in San Diego, which may have relaxed water constraints on crop choices.[104,105] Unfortunately, it is difficult to do more than conjecture without additional evidence.

This model is less representative of the Central Coast, as seen in Figure 8.14. Per-acre yields are, in general, fairly erratic. Monterey and Santa Barbara County in particular (Figure 8.14b) demonstrate essentially no upward trend in yield until the late 1960s; while this may be evidence of late adoption in Monterey, Santa Barbara crop budgets from 1960 and 1965 both include the use of MB/Pic fumigation, making the absence of an immediate yield effect unexpected. There is more visual evidence for Ventura, Santa Cruz, and San Luis Obispo (Figure 8.14a); however, the positive trend extends for a number of years outside the expected adoption period, and does not take on the expected S-curve characteristic suggested by the logistic growth model. The difference between these observations and those from the southern districts likely stems from the perennial strawberry culture that still dominated on the Central Coast. The proportion of annual planting was virtually zero during the early 1960s, limiting the potential rate of adoption as less than a third of coastal

[98] USDA, 1959 Agricultural Census, "Farms Reporting Acreage and Quantity of Crops Harvested," table 11, p.238

[99] USDA, 1964 Agricultural Census, "Acreage, Quantity, and Sales of Vegetables," table 13, p.460

[100] Both the observations and the initial t for San Bernardino and San Diego were moved forward to improve coherence with the model.

[101] R. Just and Zilberman, "Farm Size and Technology Adoption", pp. 313–317.

[102] J. M. Wilhelm, *Process for Synthesizing Chloropicrin.*

[103] USDA, 1969 Agricultural Census, "Corn, Sorghums, Hay, Field Seeds, and Strawberries: 1969 and 1964," table 21, p.287, 295

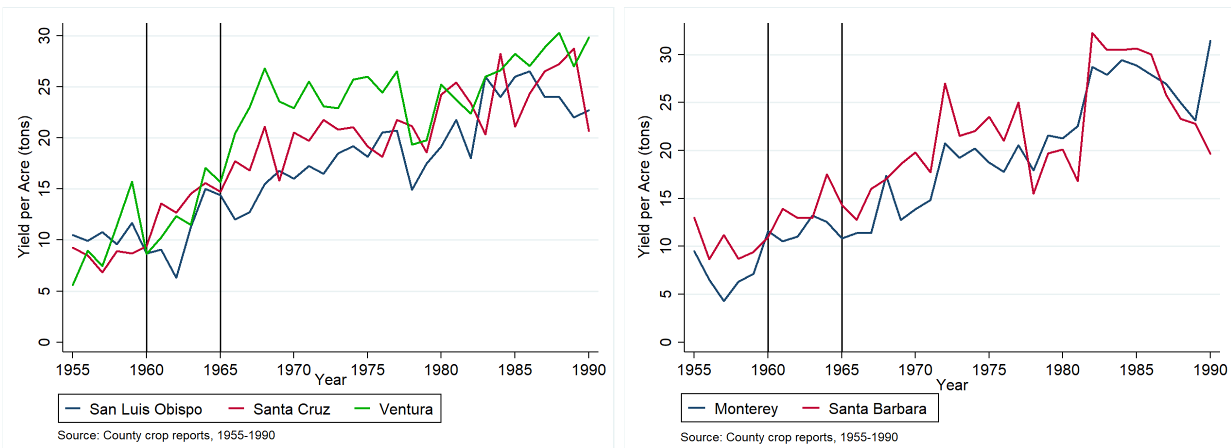
[104] Autobee, *San Diego Project*, pp. 12–14.

[105] Moon, *Agricultural Crop Report.*

acreage was in its first year at any given time.[106] The effects of soil fumigation also diminish over time; Voth et al. (1971) demonstrated that skipping a year between fumigation was associated with a 21 percent yield reduction in newly planted strawberries.[107] This evidence suggests that the inherent yield reductions perennial strawberries face due to aging would be noticeably exacerbated by increasing pest damage and resource competition over the lifetime of the planting. Together, these could have easily dampened the yield effects we would have otherwise expected to observe. The average lifetime of Central Coast acreage started to decline in the mid to late 1960s, and 80 percent was annually replanted by the late 1980s.[108]

Figure 8.14: **Central Coast Productivity, 1955-1990**

(a) Evidence of Yield Effect (b) Limited Yield Effect



San Benito is not included as the county stopped recording strawberry production in 1961.

8.7.2 Exponential Growth Model

Rather than a logistic growth model, it may be more informative to treat the data as composed of three sections - pre-fumigation, an adoption period, and post-fumigation - and fit it to an exponential model of growth instead.

We take the model:

$$Y = \alpha + \mathbb{1}_1 \beta t^{\gamma_1 + \mathbb{1}_2 \gamma_2} \tag{8.2}$$

where Y takes on the value α until some t_1, after which yields begin to increase by βt^{γ_1} until t_2. After t_2, the rate changes to $\beta t^{\gamma_1+\gamma_2}$, where γ_2 represents our belief that growth will differ between the adoption and post-adoption period of fumigation. There is also a convenient expression for the elasticity of yield with respect to time:

[106] California Crop and Livestock Reporting Service, *Strawberries, Acreage and Indicated Production.*

[107] Voth, Radewald, et al., "Effects of Successive Soil Fumigation with Methyl Bromide-Chloropicrin on Strawberry Replanting".

[108] Wells, *Strawberry Fields: Politics, Class, and Work in California Agriculture*, p. 183.

$$\frac{\partial Y}{\partial t}\frac{t}{Y} = \frac{\gamma\beta t^{\gamma}}{\alpha + \beta t^{\gamma}} : \lim_{t\to\infty} \frac{\gamma\beta t^{\gamma}}{\alpha + \beta t^{\gamma}} = \gamma \tag{8.3}$$

with γ providing a serviceable approximation of elasticity when values of α are relatively small. When $\gamma > 1$, we have increasing marginal productivity over time; below 1, it will taper off. We anticipate the latter will hold for our coastal counties.

The data was truncated prior to 1960 to exclude the short-term impact of the frozen market crash and 1961 and 1971 were chosen as the t_1 and t_2. A priori, we would anticipate $\gamma_2 < 0$, as the rate of growth is likely to decelerate following full adoption of fumigation. The regressions produce the following:

Table 8.5: **Central Coast, Exponential Growth Model**

	Coastal CA 1960-1990	Monterey 1960-1990	S.L. Obispo 1960-1990	S. Barbara 1960-1990	S. Cruz 1960-1990	Ventura 1960-1990
α	9.13*** (1.609)	10.42*** (1.646)	7.30*** (1.973)	9.92** (2.835)	9.28*** (2.189)	6.99** (2.083)
β	1.828* (0.968)	0.447 (0.399)	1.433 (1.040)	2.918 (3.216)	2.391 (1.575)	3.46* (1.870)
γ_1	0.609*** (0.173)	0.854** (0.308)	0.765*** (0.247)	0.395 (0.356)	0.596** (0.222)	0.678*** (0.189)
γ_2	0.067 (0.070)	0.239 (0.233)	-0.031 (0.083)	0.113 (0.163)	-0.033 (0.076)	-0.135** (0.062)
N	31	31	31	31	31	31
Adj. R^2	.887	.854	.809	.517	.747	.772

Standard errors in parentheses. * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$ t_0 set to 1959.

The fit of the exponential model is weaker compared to the logistic growth model - particularly with Santa Barbara - though this is not surprising given the general instability in yields over even short periods of time. While undoubtedly there are numerous effects generating these fluctuations, to some degree they are simply inherent to perennial culture, as productivity rises and falls with the cultivation cycle. Despite a less satisfactory fit, however, the parameter values are indicative of a discrepancy between county growth rates; of particular interest are those of Ventura and Monterey County, which occupy opposite ends of the spectrum. With allowances for the general inconsistency of yields, all five counties managed to achieve close to 30 tons per acre by the mid-1980s; this appears to have been a soft ceiling after which further gains became incremental, with individual counties exceeding 33 tons per acre a combined total of four times between 1990 and 2005. The rate at which they arrived at this ceiling, however, varied greatly; Ventura reached yields of over 25 tons per acre by the late 1960s, and would remain at about that level well into the 1980s. In contrast, Monterey estimates for β and γ_1 suggest it experienced a slower rate of growth during the t_1-t_2 adoption period than all other counties; its γ_2 parameter indicates acceleration, rather than leveling out, in the post-fumigation period. Interpreting the data graphically, there appears to be an uptick in annual yield increases towards the late 1970s, prior to a massive jump in the early 1980s. Other counties, with the possible exception of Santa Barbara, fall between these two growth rates.

Consistent with agricultural intensification theory, these patterns reflect urbanization rates by county that were derived by the USDA via aerial imaging. During the 1950s and 1960s, agricultural land in Ventura County was converted at a estimated rate of almost 1,600 acres annually; using 1955 as a baseline, this was a loss of slightly more than 1 percent of total cultivated acreage every year. The comparable figure for Monterey was 140 acres, or just 0.05 percent of acreage. As expected, Santa Barbara and Santa Cruz lay between these two extremes at annual rates of 0.45 and 0.2 percent respectively. Unfortunately, similar data were not collected for San Luis Obispo; however, county crop report data indicates a reduction of roughly 20,000 acres between 1955 and 1965. If we operate under the assumption that change in total agricultural acreage is a reasonable upper bound on the rate of urbanization, then this corresponds to an average annual conversion of no more than 0.8 percent, again falling between the two extremes of Monterey and Ventura. Regarding Monterey specifically, one interpretation that remains consistent with our observations is that the limited rate of urbanization not only kept land prices down, but that the apparent stability of agricultural land attracted more investment in infrastructure - resulting in substantial productivity growth relative to other districts.

8.7.3 Adoption Outside California

Outside of California, the replacement of existing rotation/migration practices with MB/Pic was minimal and generally not advised. Verticillium wilt was less severe and less frequent outside of California; warmer climates, like those in the Southeast and Gulf states, are less favorable for *V. dahliae*. Wilt infection was also not necessarily fatal, as plants with mild symptoms might make a full recovery the following year. Between this and cheaper, more readily available land, rotation was more feasible as a as a method of pest control.[109] This is illustrated by the rotation schedules put forward by the Agricultural Research Service in the 1970s; eastern growers were recommended to follow a two year rotation that did not include potatoes, peppers, or tomatoes. In contrast, the rotation length in California was a minimum of ten years, with a substantially longer list of proscribed crops.[110]

However, even if soil diseases had been equally as severe in these states, growers would have been unable to justify fumigating with MB/Pic as the yield effect from damage control could not have generated sufficient income to offset the cost. Given their relative productivity, growers in the Pacific Northwest would most likely have experienced the largest financial benefits from fumigation outside of California and Florida. Oregon field trials of MB/Pic in the early 1960s suggested damage control would result in a 30 to 50 percent increase in productivity, bringing yields from 3 to 4 tons per acre up to 4 to 6. At prevailing prices, this amounted to an additional $250 to $500 in income; given that fumigation was priced between $350 and $400 an acre, the profit margin of treatment was very thin.[111] Compared to California, Oregon also had significantly lower labor expenditures, reducing the potential benefit

[109]Scott and Darrow, *Growing Strawberries in the Southeastern and Gulf Coast States*, p. 26.

[110]Agricultural Research Service, *Strawberry Diseases*, pp. 10–11.

[111]Anonymous, *Oregon's Agricultural Progress: Soil Fumigation for Small Fruits*, p. 5.

from substitution. Lower productivity outside of the Pacific Northwest made adoption even less tenable; agricultural bulletins from states like Ohio, Illinois, and Michigan recommended against fumigation with MB/Pic even where production was disrupted by verticillium wilt or other soil-borne fungal diseases like red stele (*Phytophthora fragariae*).[112,113] The primary methods of control remained avoidance, rotation, and, when available, cultivars with greater tolerance to disease.

[112]Zych and Powell, *Strawberry Growing in Illinois*.

[113]Jones, *Fruit Crops Research: Root Diseases of Strawberries*.

Chapter 9

Conclusion

The intent behind constructing this economic history was to understand and provide context to the decisions and trends that have occurred within the strawberry industry, an approach inspired by Alan Olmstead's contributions to the literature of economic and agricultural history. Over the course of this narrative, we have observed the development of the strawberry from its origins as a mixed forage/garden crop to a multi-billion dollar industry and one of the most valuable agricultural products in the country. Production, once widely dispersed throughout the country, is now highly concentrated in just a handful of districts in California and Florida. Average productivity increased by more than an order of magnitude over the 20^{th} century. While acreage requirements remain small, other characteristics of production that attracted the earliest growers have been radically altered. Minimal-investment cultivation on marginal soil has disappeared entirely; strawberries are now one of the most capital-intensive crops grown in the United States, and are grown under conditions that are as near to ideal as possible. We will conclude this narrative with a short discussion regarding the results of this approach, potential changes to the industry as it adjusts to the phaseout, and some of the questions still left unanswered.

9.1 Lessons From the Historical Perspective

While many aspects of strawberry cultivation have changed over the course of this narrative, there are three that have remained virtually immutable. The first of these is the extreme perishability of the fruit, which continues to influence the entirety of strawberry cultivation and is inextricably linked to the structure of its supply chain. The second is the role of capital investment, which serves as a means to overcome perishability; this has included new shipping methods, refrigerated transit, cold storage at the point of purchase, and the proliferation of cooling and processing facilities. Improved transportation in particular has allowed production to shift to districts with the largest comparative advantages; referring back to von Thunen's model, the circle of production that was originally limited to the immediate vicinity of urban centers now encompasses the entire country. The third is the value of geographic permanence, which stems from the necessity of capital and its associated fixed costs - and, by extension, perishability. The combination of large investments in immobile on-farm capital - irrigation equipment, picking stations, shipping infrastructure - and the importance of nearby off-farm capital - cooling facilities, processors, equipment rental services - encourages growers to cultivate high value crops repeatedly in the same location. Agricultural extension services recommend growers contract out to external services to oversee shipping and sales, which puts further constraints on a grower's ideal location and encourages consistency in production. The benefits of repeated cultivation also extend to knowledge accumulation of local conditions, including soil type and quality, relevant pathogens, and salt content of the water supply - factors which affect a grower's choice of cultivar. This also affects a grower's decision-making; on short-term leases, longer-term investments in land or pest management are positive externalities that will be under-supplied.[1,2] This leads us to the critical takeaway from these aspects of production: while fumigation enabled monoculture, the propensity to adopt it has always existed within the industry.

9.1.1 A Multidisciplinary Approach

This narrative has examined the history of the strawberry primarily through the lens of agricultural economics; however, examining and incorporating work from adjacent disciplines has also identified potentially faulty assumptions or gaps in knowledge that exist in previous literature. We have already discussed one such issue in an earlier section: the conflation of acreage effects from the frozen market crash in the late 1950s with methyl bromide post-1960. This has led to authors overestimating the impact of one of the two individual events, as seen in both Wells (*Strawberry Fields*) and Guthman (*Wilted*).[3,4] The history of fumigation itself is also illustrative with regards to pesticide development. While there is a growing contemporary focus on the human and ecological health impacts of pesticide use, innovations in the field have improved operator safety and reduced non-target damage, particularly when compared to the original chemicals and application methods. We should remain cognizant, however, that both fumigation as well as the system of monoculture it has enabled still come at a environmental - and at times, human - cost.

Some of the gaps caused by insufficient contextual information are more comprehensive. For example, Guthman suggests the possibility that "modern crop breeding itself has weakened the [strawberry] plant" with regards to fungal pathogens by disregarding traits that impart disease tolerance, reasoning that "the scientific focus on productivity and marketability has left such questions to speculation."[5] This neglects several elements of the relationship between resistance and commercial cultivation, not the least of which is the existence of resistant strawberry cultivars which have been introduced to growers but subsequently failed to achieve a foothold commercially. It also glosses over other salient issues in replacing resistance with chemical control. The expression of resistance for a pest or pathogen is not complete protection against the specific pest; in addition, resistance to one pest does not indicate general tolerance of others, as California growers discovered after adopting the Nich Ohmer. These traits also have a limited shelf-life, and are eventually overcome by new strains of the fungal pathogen they are meant to defend against; this process is further

[1] *Interview with Peter Henry, USDA ARS.*

[2] *Interview with Oleg Daugovish, UC Cooperative Extension (Ventura County, CA).*

[3] Wells, *Strawberry Fields: Politics, Class, and Work in California Agriculture*, pp. 33–34.

[4] Guthman, *Wilted*, p. 160.

[5] Ibid., p. 73.

accelerated by monoculture, and possibly through irrigated cultivation.[6,7] While broadening this perspective with more context is unlikely to change the key arguments of Guthman's work, it will arguably provide a better starting point from which to search for a solution.

9.1.2 The Industry Today

Technological progress has not altered the fundamental characteristics of strawberry production, but it has still resulted in extensive changes to how production is carried out. Individual farms are now typically no less than 30 to 40 acres at minimum; in regions like Ventura County and the Santa Maria Valley, this figure is closer to 70 or 80.[8,9,10] It is worth mentioning that while farm size is now an order of magnitude larger than it was in the 1940s, there is still a limit to what an individual grower can effectively cultivate; past a few dozen acres, a grower will need to start contracting out part of their operation. Precooling in makeshift wooden sheds prior to afternoon shipping has been replaced by directly loading trucks, which are themselves commonly equipped with refrigeration. Minimizing distance remains critical; there is typically no more than fifteen miles between a strawberry farm and the nearest cooling facility, and trucks are ideally loaded and unloaded within an hour.[11,12] The adoption of drip irrigation has allowed growers to start cultivating steeper land, as well as apply both fertilizer and pesticides through the drip tape ("fertigation" and "chemigation"). Seasonality still has a strong influence over the market prices a grower receives, although now some growers own multiple, non-contiguous plots at different latitudes in order to space out their own production timing.

Production costs have also risen significantly over this period due to the shift in location as well as the increased capital intensity. Strawberry acreage in California is still primarily rented, and the cost varies by district, and is generally on the order of a few thousand dollars per acre; in 2011, cost study estimates of land rent ranged from $2,200 per acre in the Santa Maria Valley to $3,500 in Ventura County. Including labor expenditures for harvest, costs of production varied between $25,000 and $50,000 per acre depending on the total yield. Like farms, nurseries have also become significantly larger, with those that own their own cooling facilities are either part of a co-op or close to 1,000 acres in size. In addition to greater capital efficiency, larger strawberry operations benefit from more permissive lending criteria and are less burdened by the overhead that has come to characterize modern agricultural production. Off-farm, cooling facilities now operate year-round, moving thousands of boxes of strawberries daily to supply both national and international consumers; a handful of these larger coolers can suffice for an entire county.[13,14,15]

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[6] *Interview with Gregory House, UC Davis.*
[7] Bell, "Verticillium Wilt", p. 89.
[8] Bolda, Tourte, et al., *Sample Costs, Central Coast Region.*
[9] Daugovish, Klonsky, and Moura, *Sample Costs, South Coast Region.*
[10] Dara, Klonsky, and Moura, *Sample Costs, Santa Maria Valley.*
[11] *Interview with Gregory House, UC Davis.*
[12] *Interview with Oleg Daugovish, UC Cooperative Extension (Ventura County, CA).*
[13] *Interview with Peter Henry, USDA ARS.*
[14] *Interview with Steven Fennimore, UC Davis.*
[15] *Interview with Roger Hamamura, Planasa Nursery.*

9.2 Looking Forward

Although strawberry growers' access to MB/Pic fumigation ended in 2017, it will take some time for the effects of the phaseout - biological as well as economic - to fully manifest.[16] Given the economic value of monoculture to growers, it is unsurprising how much effort has been expended in attempting to preserve it; to this end, growers and researchers have explored several chemical and non-chemical alternatives.

The search for a replacement fumigant for methyl bromide has met with limited success. Currently, chloropicrin itself is the most widely used fumigant in California strawberry production, and has seen progressively greater use as methyl bromide availability declined. It is also frequently combined with 1,3-Dichloropropene for additional control of nematodes. Methyl iodide was at one time a promising alternative, but evidence of its toxicity to humans and significant public backlash to its registration caused its parent company Arysta Lifescience to withdraw it from the market. Other fumigants, seen in Figure 9.1, are generally less effective or their use is in some way objectionable.[17,18,19]

Figure 9.1: **Soil Fumigant Efficacy**

Fumigant active ingredient	Fungi	Nematodes	Weeds	Insects	Mobility in soil	In use as preplant soil fumigant since
Chloropicrin	++++[a]	++	++	++	++	1927
Methyl bromide	++++	++++	+++	++++	++++	1958
Methyl bromide + chloropicrin	++++	++++	+++/+	++++	++++	1961
1,3-Dichloropropene	+	++++	++	++	++	1954
Methyl isothiocyanate generators						
Dazomet	+++	+++	+++	++	+	1967
Metam potassium	+++	+++	+++	++	+	1973
Metam sodium	+++	+++	+++	++	+	1975
Allyl isothiocyanate	+++	++++	++	++	+	2013
Dimethyl disulfide	+++	++++	++	++	++++	2010
Ethanedinitrile	++	++	++	++	++	2017
Methyl iodide	+++	++++	+++	++++	++++	Registered in 2008; withdrawn in 2012

[a] ++++ = excellent; +++ = good; ++ = fair; and + = poor.

Source: Holmes et al, *Strawberries at the Crossroads*, 2020.

Non-chemical methods of control generally face more barriers to their adoption. Direct physical methods - flooding or raising the temperature of the soil - are relatively simple to implement and reasonably effective. However, heating the soil is either climate-dependent (soil solarization) or expensive (steam), and flooding occupies the land for several months and is highly water-intensive. Rotations with rice paddies have been successfully used to control verticillium wilt in strawberries, but did so over a four-year rotation cycle. Rotations with

[16] *Interview with Oleg Daugovish, UC Cooperative Extension (Ventura County, CA).*

[17] G. Holmes, Mansouripour, and Hewavitharana, "Strawberries at the Crossroads".

[18] Hueth et al., "Analysis of an Emerging Market: Can Methyl Iodide Substitute for Methyl Bromide?"

[19] Guthman, "Strawberry Growers Wavered Over Methyl Iodide, Feared Public Backlash".

broccoli are particularly effective, as not only is it resistant or immune to *V. dahliae* strains, incorporating its residue into the soil reduces *V. dahliae* inoculum through the chemicals it releases into the soil as it decomposes. Unfortunately, cost study estimates from 2017 suggest cultivating broccoli on current strawberry acreage would generate negative returns.[20,21,22,23] Anaerobic soil disinfestation (ASD) involves introducing organic amendments to the soil and allowed to decompose; the soil itself is covered by a plastic film, creating an anaerobic environment which is suppressive to a wide range of crop pests. ASD is also demonstrably effective against *V. dahliae*, but is roughly a third more expensive than current fumigation treatments while also time-sensitive and temperature-dependent; farmers in California need to complete ASD treatment before soil temperatures fall below 17°C. However, ASD also generates heat, meaning that growers in Florida have to adopt darker-colored plastics for strawberry cultivation or risk inhibiting crop growth due to excessive soil temperatures.[24,25]

It is entirely possible that some combination of these alternatives is sufficient to preserve the existing system of monoculture, which would hinge on their ability to keep pest pressure from escalating past some critical threshold while remaining economically viable. Failing this, we suggest that the industry may reorient itself in one of a few different ways. Assuming a complementary effect between MB/Pic alternatives and short rotations, we may see strawberry production begin to exit the coastal region and move inland to agricultural districts where larger quantities of less expensive land are available. Replicating current production under a short rotation system would require three or four times as much acreage even before compensating for any reductions in yield. If the shift inland is great enough, it would also start to compress the strawberry season. It is also possible that the industry might begin to reverse some of the changes it made post-1960, with other states re-entering commercial production depending on how California yields are affected and the magnitude of additional shipping costs caused by disrupting the current system. Yields outside of California, Florida, and the Pacific Northwest have remained virtually stagnant since the early 20$^{\text{th}}$ century, but it also costs around $10,000 to ship a truckload of strawberries across the country; if strawberry prices increase as a result of changes in California, there may be an economically viable niche for smaller production districts serving nearby cities. In this scenario, however, holding supply constant would require a far greater amount of land than is currently under strawberry cultivation, particularly if growers are engaging in rotation, and would also re-introduce seasonality into consumption.[26]

Rather than transitioning back to an earlier structure, it is also possible that agricultural and technological development will result in yet another transformative period within the industry. For example, strawberries are one of the few crops for which vertical farming is currently both economically and physiologically feasible. In exchange for substantial capital investment, vertical farming dramatically reduces land requirements and allows for precise

[20] Koike and Subbarao, "Broccoli Residues Can Control Verticillium Wilt of Cauliflower".

[21] Shetty et al., "Mechanism of Broccoli-Mediated Verticillium Wilt Reduction in Cauliflower".

[22] Zavattaa et al., "Integrating Broccoli Rotation, Mustard Meal, and Anaerobic Soil Disinfestation to Manage Verticillium Wilt in Strawberry".

[23] Tourte et al., *Sample Costs of Broccoli.*

[24] Momma et al., "Development of Biological Soil Disinfestations in Japan".

[25] Shennan et al., "Anaerobic Soil Disinfestation for Soil Borne Disease Control in Strawberry and Vegetable Systems: Current Knowledge and Future Directions".

[26] *Interview with Roger Hamamura, Planasa Nursery.*

control over factors such as irrigation, climate, and pest pressure. Effectively, this would allow other states to replicate some of the conditions that make California so successful without being tethered to a specific location. Highly localized production - similar to how the industry was originally organized - would circumvent issues with perishability, transportation costs, and the trade-off between cultivar firmness and its other qualities without causing yields to diminish. This is necessarily an expensive method of cultivation and does not benefit from the same economies of scale as field production; however, as the costs of vertical farming decrease over time, it may become a secondary stream of production.[27] This is somewhat akin to the system that has emerged in Japan, which provides our suppositions with some supporting evidence. Strawberry cultivation occurs almost entirely within greenhouses, with the attendant control over growing conditions this provides. Growers employ various cultivars as well as climate and photoperiod manipulation techniques to extend the harvest season compared to field production; this can range from an additional 5 to 6 weeks or up to four or five months if more intensive forcing techniques are used. Domestic cultivars also tend to be softer and have a shorter shelf-life; there is also a premium market for particularly high-quality produce. In addition, average Japanese yields as of 2019 are slightly higher than 12 tons per acre; although this is well below yields in California, it is well in excess of all other states.[28,29]

9.3 Questions and Future Research

Due to data limitations and time constraints, there are still a number of questions that remain at the conclusion of this dissertation. Methyl bromide is thought to have dramatically increased land rent in coastal agricultural districts by making them more attractive for strawberry production (as well as increasing yields). We have made a first pass at identifying fumigation adoption patterns; unfortunately, the California Department of Pesticide Regulation does not have data prior to 1970, and crop report data are only disaggregated to the county level. However, if sufficient leasing data are available from the 1950s and 1960s, it may be possible to generate a very rough estimate of the effect of fumigation on land prices. It would also be interesting to perform an environmental impact analysis comparing the existing industry to a hypothetical one where acreage returned to a pre-WWII distribution but production was held constant. Concentrating acreage in California has generated environmental costs from both fumigation and greenhouse emissions from transportation, but the industry's current organization is also land sparing. Strawberries are unique in the degree of their perishability; extending this historical narrative and economic analysis to other high-value, verticillium-sensitive crops would be useful as a means to support - or contradict - our findings regarding the relationship between perishability, capital investment, and monoculture.

[27] Benke and Tomkins, "Future Food-Production Systems".

[28] Yoshida, "Strawberry Production in Japan".

[29] Sugimoto, *Strawberry Market Situation*.

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