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Seeing Water in Food: A Hydrosocial Analysis of Almond Agriculture in California and Spain

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This article illustrates how food is *hydrosocial*: a medium through which people and water are entangled, with world-shaping consequences. We bring food geography and water geography into closer dialogue, developing a framework to analyze how water becomes embedded in the production of particular foods. Our focus is the rise of irrigation-intensive almond production in California and Spain. For millennia the almond was a drought-tolerant plant supporting low-input, resilient agriculture in marginal landscapes. Now, over 90 percent of the world's almonds come from heavily irrigated monocrops that deplete local water and are vulnerable to climatic shocks. Narrating almond intensification as a process of hydrosocial reconfiguration, we offer three insights. First, we trace how a food's water needs are not biologically given but emerge within specific hydrosocial configurations. Second, we show how efforts toward efficient water use can exacerbate the vulnerabilities they promise to resolve. Third, we show how hydrosocial logics travel through food, territorializing new landscapes and generating uneven outcomes in distant places. We conclude by drawing out implications for geographical research on food–water relations. **Key Words:** *agri-food system, almond, hydrosocial cycle, irrigation, political ecology.*

This article asks how the almond (*Prunus dulcis*)—a drought-tolerant tree that originated in the mountain deserts of western Asia—became an infamous “thirsty crop” (Philpott 2014) dependent on copious irrigation. For millennia, almond trees were exceptionally tough, tolerating long, hot summers with as little as 200 mm of annual rain and frequent droughts. Now, heavily irrigated orchards supply over 90 percent of the world's almonds. In California, the crop's industrial epicenter, they use more than 1,400 mm of water per annum (Fulton, Norton and Shilling 2019). Irrigated monocultures have made almonds a \$9 billion industry in the state, where they cover a greater surface area than any other crop (Matthews, Baratahvil, and Sumner 2020). The industrial almond assemblage—its chemical regimes, rootstock, geographies of production, land values, agronomic guidelines, and investor expectations—has evolved under the assumption of water's continued abundance. Similar intensive systems have recently emerged in Spain, upending rain-fed almond production that has

persisted for centuries. As California producers drained ancient aquifers during recent droughts, almonds came to symbolize the extractive nature of industrial agriculture (Arax 2018; Reisman 2019).

The relationships between water and foods like almonds are typically assessed, represented, and governed through quantitative metrics and data (Linton 2010; Meehan et al. 2023). As Molle, Lankford, and Lave (2024) observed: “people expect information about water to be conveyed through numbers, in terms of depth, stock, flow, chemical or biological characteristics, or associated economic values, costs and benefits” (325). On the production side, these include evapotranspiration rates, crop water requirements, and irrigation withdrawal estimates—all pillars of agronomic knowledge intended to structure water's rational use. On the consumption side, quantification centers on “virtual water”: “the volume of freshwater used to produce the product” (Hoekstra and Chapagain 2006, 36). Originally designed to influence trade policy by highlighting the invisible water embedded in commodities traveling across

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borders (Allan 2003), virtual water has since become a widely accepted sustainability metric, often known as a food's "water footprint" (Freidberg 2015).

These "water numbers" (Molle, Lankford, and Lave 2024) have become tremendously influential, directing policies, informing consumer food decisions, and facilitating analyses that reveal how global commodity exports can drive local water scarcity. Metrics can also depoliticize water, however, rendering complex political ecologies into simplified technical accounts that obscure the cultural, political, economic, and ecological processes shaping food–water relations (Bakker 2012; Barnes 2013; Meehan et al. 2023; Molle, Lankford, and Lave 2024). Some suggest that virtual water conceals how global water flows are increasingly controlled by governments and agro-industries (Beltrán and Kallis 2018). Critiques of "rational use" sustainability models make a parallel point: Efficiency means different things to different actors at different scales, and this flexibility allows agencies, agribusinesses, and regulators to endorse it while pursuing incompatible ends (Lankford et al. 2020; Anderson and Cantor 2024). Others caution that framing water use in terms of output per unit implicitly favors intensive agriculture, as higher yielding systems appear more efficient even as they consume more water overall—reinforcing a Green Revolution logic in which intensification is the precondition for economic growth and food security (Trottier, Leblond, and Garb 2020; Petit et al. 2021).

Fundamentally, quantitative approaches struggle to capture how water and food coconstitute one another. We argue instead that food is *hydrosocial* (cf. Budds, Linton, and McDonnell 2014). Water and the foods it produces make and remake each other through situated relations of political economy, ecology, and agriculture. Tracing the rise of irrigation-intensive almonds in California and Spain, we draw together concepts from water and food geography to analyze distinct *hydrosocial configurations* of almond agriculture: the historically contingent, geographically specific, and institutionally stabilized assemblages of practices, technologies, discourses, and power relations that govern how a particular food is produced in relation to water. We argue that water is embedded not only in the infrastructure of production but in the taste profiles, economic rationalities, and social values through which food is qualified and made to travel. We suggest that relatively stable spatial manifestations of such configurations play key

roles in the production of "hydrosocial territory" (Boelens et al. 2016). Tracing almond hydrosocial configurations reveals their varied consequences, from ecological precarity and dispossession to sustaining resilient livelihoods.

The following section elaborates this framework through a brief review of food and water geography. We then narrate the almond's transformation from drought-tolerant tree to "thirsty crop," first in California and then in Spain, where irrigated monocrops now expand alongside a persistent rain-fed configuration organized by its own vernacular water logic. From this account the discussion develops three contributions: that a plant's water needs are not biologically given but emerge within hydrosocial configurations; that schemes promising to resolve ecological vulnerability through "efficient" water use can inadvertently deepen it; and that hydrosocial logics travel through food, territorializing distant landscapes and generating uneven outcomes. We conclude with implications for geographical research on water and food.

The Geographies of Water and Food

Geographers have long considered the centrality of water to food production. Irrigated agriculture accounts for around 70 percent of global freshwater use (McDermid et al. 2023) and generates an estimated 40 percent of the world's food (Wada et al. 2010). Human alteration of water flows has profound and uneven social-environmental impacts. Irrigation features prominently in projects of state-making, modernization, and settler-colonialism (Swyngedouw 2009; Curley 2021), its infrastructure serving to consolidate state and corporate power (Meehan 2014; Birkenholtz 2016). Dams and other infrastructure can limit aquifer replenishment, degrade riparian habitats, constrict river connectivity, and reduce nutrient distribution on which plant and animal species depend (Jägermeyr et al. 2017). Irrigation projects frequently provoke water conflicts (Rodríguez-Labajos and Martínez-Alier 2015), supporting resource accumulation by local elites and external actors while stranding marginalized communities without water access (Meehan et al. 2023; Anderson and Cantor 2024).

In presenting food as hydrosocial, this article draws on and develops a growing body of scholarship exploring the cross-scalar relations between water

and food (e.g., Mollinga 2014; Trottier, Leblond, and Garb 2020; Birkenholtz 2023). Our aim is to further bridge food geography and water geography, two subfields committed to human–environmental dynamics whose historical trajectories have nonetheless produced distinct foci and relatively limited dialogue. Water geography has richly theorized how governance, culture, infrastructure, and technology underlie irrigation (Linton and Budds 2014; Liao and Schmidt 2023), but food itself tends to appear as an output of these hydrosocial relations rather than a differentiated force shaping their configuration.¹ Food geography, for its part, attends closely to diverse elements of agrifood assemblages—the practices and technologies of production, the materialities of foodstuffs, the affective palates of consumers (Kneafsey et al. 2021; Yap 2023)—yet has rarely made water itself a differentiated analytic object, instead treating it as one input among many.² Neither emphasis is a failing. They are the natural foci of fields with different starting points. Bringing the two together provides an opportunity to trace how water circulates through differently configured agrifood assemblages, constraining some political ecologies and enabling others.

We start from the foundational concept in critical water geography of the *hydrosocial cycle*, or the “socio-natural process by which water and society make and remake each other over space and time” (Linton and Budds 2014, 170). Developed partly out of frustration with traditional hydrological science practice (Budds, Linton, and McDonnell 2014), the hydrosocial cycle considers how water use and management encompass not only infrastructure, hydrological expertise, and H₂O, but also human values, cultural institutions, political power, economic rationales, and social behavior (Linton 2010; Bakker 2012; Mollinga 2014). Geographers have recently employed hydrosocial thinking to understand how water is enrolled in the production of nature through modernist logics, which serve to silence diverse other ways of knowing and relating to water (e.g., Liao and Schmidt 2023). Hydrosocial geographies narrate how the uneven circulation of water configures socioeconomic inequities and environmental harms (Meehan et al. 2023). Here water emerges as an “uncooperative commodity” (Bakker 2003) with local embeddedness and liquid materiality that frustrate projects toward its enclosure.

A hydrosocial lens helps visualize the historical geographical processes through which water and society are coconstituted, offering techniques to trace the political economic, cultural, and material relations that underlie hydrological knowledge (Linton and Budds 2014). It frames water struggles as deeper contestations over territory and identity (Budds, Linton and McDonnell 2014), with analyses trained on the configuration of the hydrosocial networks through which water is governed and the distinct hydrosocial territories these networks produce (Boelens et al. 2016). Key to our study of almonds is hydrosocial territorialization, the process by which competing actors advance territorial projects that align water flows, infrastructure, institutions, and knowledge around claims to water control (Boelens et al. 2016; Alba et al. 2025).

We find a parallel set of tools in food geography, which expands the political economy of agriculture to the broader social, political, economic, cultural, and environmental relationships that structure food systems from “farm to fork” (Kneafsey et al. 2021). Cook’s (2004) “follow the thing” approach is a canonical example, inspiring research that traces how texts, images, knowledge, and technologies circulate alongside goods, capital, and labor to facilitate food’s uneven globalization. Departing from the orthodox view of food systems as tightly coordinated chains of actors operating in rational economic spheres, recent work traces how food is entangled in relations linking production and consumption, using multisited ethnography to surface the contradictions and unlikely connections that drive capitalist agrifood trajectories (Freidberg 2015; Yap 2023).

Geographers increasingly approach agrifood systems as sociomaterial assemblages, marked by contingency and heterogeneity even as they reflect the homogenizing ambitions of global capital (Werner, Berndt, and Mansfield 2022). A key influence for us is research documenting how the relations underlying intensive production generate their own crises. For example, the privatized breeding, chemical dependence, and continuous production that made California strawberry production so lucrative also produced the pathogens that now threaten the industry (Guthman 2019). In short, food geography parallels critical water geography in important ways. It holds together the indeterminacy of agricultural trajectories while acknowledging the structuring

force of political economy, pluralizing agency without abandoning concern for uneven development and ecological precarity (Galt 2013; Werner, Berndt, and Mansfield 2022).

Recent work begins to draw the two subfields together. Trottier, Leblond, and Garb (2020) demonstrated how date palm plantations reshape land and water rights as well as wider social relations in Palestine. Supported by international donors and agribusiness who employ discourse about water efficiency to broker capital-friendly water agreements, date palms displace local subsistence farming activities, exacerbating food and housing insecurity for Palestinians (Trottier and Perrier 2018). Birkenholtz (2023) revealed how the efficiency gains of drip irrigation in India depend on low-caste female laborers, whose underpaid work enables denser planting, fewer fallow periods, and the cultivation of crops with extended harvest seasons, such as green chilies. Kay, Knudson, and Cantor (2024) traced a longer arc in Hawai'i, where an extensive system of irrigation ditches diverted land, labor, and water to sugarcane, displacing indigenous agroecologies—and where that same infrastructure obstructs contemporary efforts to move beyond plantation agriculture even after the sugar industry's collapse.

Our article applies and develops food–water scholarship by following the evolving relationship between water and almonds across two settings. Tracing how almonds became a thirsty crop (first in California, then in Spain), we show that water is embedded not only in sites of food production but in the economic rationalities, taste profiles, and social values that traverse supply chain stages across different continents. We contrast two almond hydrosocial configurations. In the irrigated configuration, water streamlines industrial logic, disciplining production in pursuit of maximal profit. In water-limited regions, the almond resists industrial simplification, offering resilience to climatic and economic shocks in place of high yields and standardized nuts. Following the almond as a hydrosocial commodity across these settings reveals a geography of uneven development that the politics of water or food alone cannot explain.

Methodology

Our analysis pairs a critical reading of industry and historical documents with ethnographic material from site visits and interviews. We approach the two

cases through complementary methods: California primarily through historical and archival analysis, as transformation of the almond into a “thirsty crop” is complete, and Spain primarily through ethnographic field work, as there the irrigated and rain-fed configurations coexist and compete in the present. In Spain, the first author conducted semistructured interviews with eighty-three almond sector actors across the major almond regions (especially Catalonia, Andalusia, and the Valencian Community) during thirteen months of field work across four visits between 2019 and 2025. Respondents included almond producers, investors, processors, wholesalers, agronomists, government experts, and employees of cooperatives, nurseries, agri-tech companies, insurance brokers, and almond milk companies. Field work initially examined the sector's broader transformation, including the rise of almond milk. The centrality of water and of the California model of intensive production emerged inductively as a dominant theme, directing our attention to water's role in shaping the historical trajectory of almond production.

For the California case, we conducted a close reading of industry and government documentation from the nineteenth century to the present, drawn from archives in California and online, alongside fourteen interviews with contemporary growers, agronomists, and industry actors. Materials—interview transcripts, government documents, historical maps, agricultural journals, and corporate records—were coded thematically. Water's entanglement with agronomic knowledge, production geographies, and almond quality emerged as a central axis, guiding further field work and archival research at Spain's Ministry of Agriculture and regional libraries. Together, the two cases offer complementary vantages on hydrosocial reconfiguration: California reveals how food–water relations are remade over time and Spain shows how divergent configurations coexist and compete in the present.

From Tough Tree to Thirsty Crop

Because the almond tree can live from year to year under adverse moisture conditions, many erroneous opinions arose as to the possibility of growing a profitable crop where available soil moisture was lacking. The almond became known in California as a

“tough” tree and was planted on a commercial scale even in desert conditions.

—Milo Wood, horticulturalist, Bureau of Plant Industry, U.S. Department of Agriculture (Wood 1937, 20)

Originating in the alpine deserts of present-day Syria and Iran, almond trees evolved to tolerate harsh conditions (Gradziel 2011). Their deep root systems secure access to nutrients and water even on poor, rocky land. They tolerate scant rainfall and drought, excluding the salts that accumulate in arid soils, and closing leaf stomata as summer temperatures climb, halting vegetative growth and shedding leaves rather than risking hydraulic failure (Bakhtiari et al. 2025). Almonds traditionally thrived in marginal environments, often succumbing to fungus, pests, or rot where water is too plentiful (Gradziel 2011). A uniquely low-risk source of shelf-stable protein, the almond was valued by resource-poor peasants across arid and semiarid Asia and the Mediterranean (Murray et al. 2019; Morey and Fornés 2021). Here an almond hydrosocial configuration emerged over millennia, defined by uncertain and scant water, limited capital, and a prioritization of resilience over yield. A coordinated repertoire of practices—wide tree spacing, wild almond rootstock with a deep taproot, terracing to control the flow of rainwater, aggressive pruning to reduce evapotranspiration—treated water as an uncertain input that must be navigated rather than overridden.

California almond producers initially embraced this rain-fed configuration, too. By the close of the nineteenth century, the almond’s tolerance of poor soils and low rainfall had earned it a reputation as a “tough tree” (Wickson 1889, 513). Planted in sandy soils where more water-demanding trees like peaches would not grow, rain-fed almonds boomed in the early twentieth century (Wood 1937). Growers typically grafted cuttings imported from Europe, a technique recognized to improve drought tolerance (Wickson 1889). Mediterranean varieties presented obstacles to industrialization, however. They grew too slowly, yielded too little, bloomed erratically, and produced nuts of inconsistent size, shape, and taste (Corsa 1896; Wood 1924). These were perilous traits in California, where agriculture was already a heavily capitalized sector geared toward investor profit, and where specialty crops such as oranges, peaches, and lettuce had already industrialized (Stoll 1998; R. Walker 2004).

Moreover, industrial efficiency was viewed as the only way for California to compete with the European almonds that dominated the U.S. market (Riley 1948).

An industry-ready almond appeared with the *Nonpareil* (Figure 1), a variety developed in 1879 by breeder A. T. Hatch. *Nonpareil* boasted vigorous growth and heavy, uniform crops. In a U.S. Department of Agriculture (USDA) bulletin, Wood (1924) called it “the best of all varieties in California,” noting that although it was not the most flavorful almond, its paper-thin shell broke cleanly, leaving large, uniform kernels with distinctively smooth skin—qualities that made *Nonpareil* visually appealing and easy to process. It quickly became the gold standard of almond quality and the flagship of the California Almond Growers Exchange (later Blue Diamond Growers; Adams 1927). Unlike in the Mediterranean orchards of the time, rain-fed almonds were no marginal venture but a magnet for capital (Vaught 1999). Yet even as a capitalized, investor-oriented crop, almonds were seldom irrigated. Their roots were prone to rot, and rainfall produced yields considered acceptable at the time (Wood 1937). Promoters sold California almond land to distant investors on the explicit promise of immense and stable profits without irrigating (Figure 2).

Almonds were the conspicuous holdout in an increasingly irrigated valley. Yet, as irrigation spread across California for other crops and the industry’s expectations of consistent yields of uniform nuts hardened, the rain-fed almond came to look financially risky, its yields and kernel size fluctuating with the weather (Wood 1924). The USDA and land grant university system, working closely with the industry, sought to engineer that risk out of the crop, and their trials showed yields rising steeply under irrigation (Fortier 1927). By the 1930s, water had been recast as the almond’s vital limit, a reframing that depended on and helped justify the newly commercial-scale availability of deep-well turbine pumps (Wood 1937). A crop once thought to require under 400 mm of winter rain and to suffer where water tables were too high (Taylor 1918; Tufts and Philp 1922) was soon governed by a new agronomic dogma—that “good almond crops cannot be expected without irrigation, even on satisfactory soils” (Wood 1937, 20)—propagated through California Agricultural Extension Service publications such as *Almond Culture in California*. From this

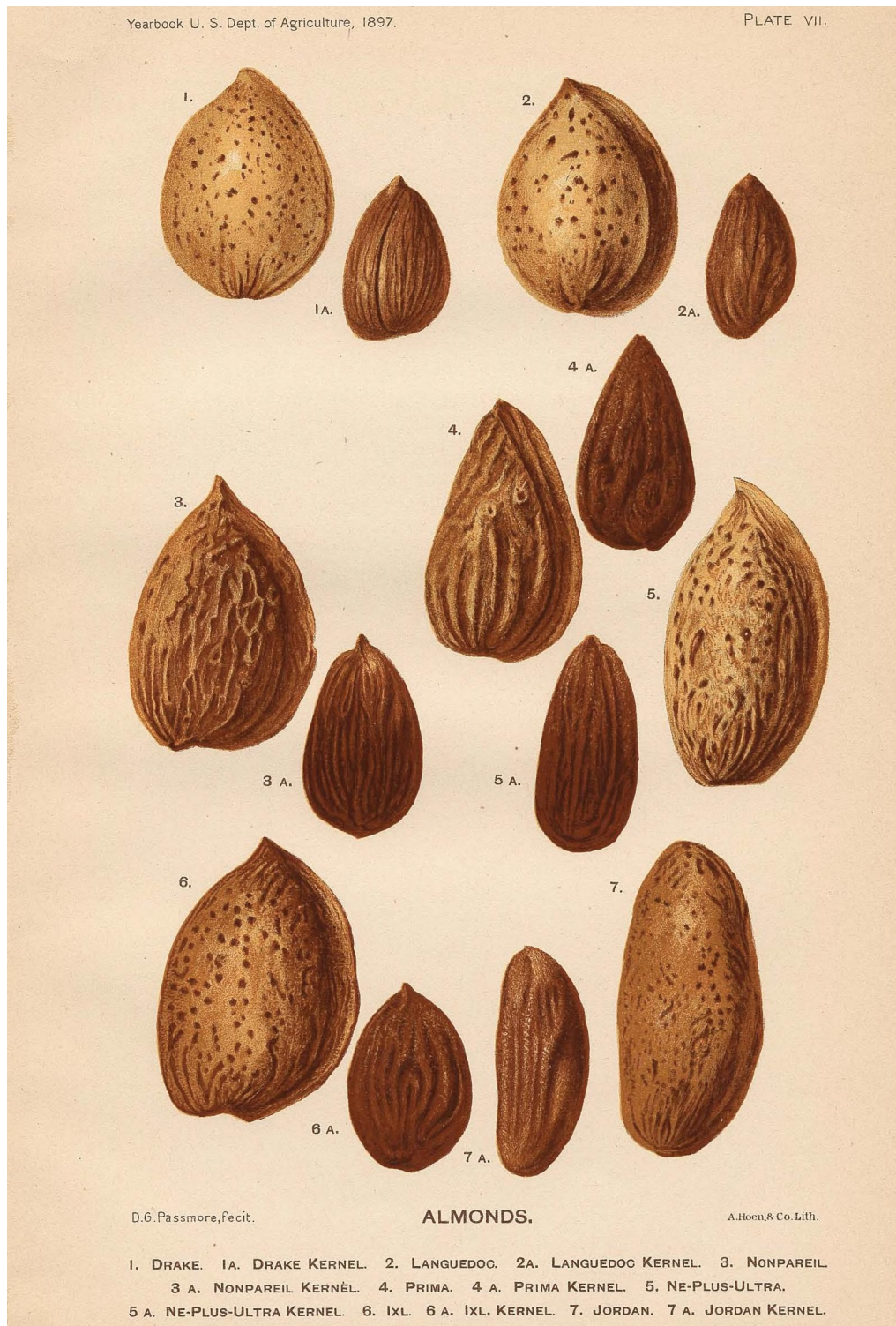


Figure 1. Shells and kernels of Californian and European almond varieties. Source: “Almonds,” Plate VII (p. 336), *Yearbook of the United States Department of Agriculture 1897* (USDA 1898). Chromolithograph by A. Hoen & Co. after a watercolor by D. G. Passmore.

point, almonds, their experts, and their growers all followed the water, setting in motion a radical reconfiguration of the almond’s hydrosocial life.

Successive irrigation technologies did not so much transform almond geography as give capital new means to remake it. Each innovation opened

New Almond Tract

At Paso Robles, California

No Irrigating—No Fertilizing—No Crop Failures—Big Profits

We have repeatedly stated that desirable almond land in California is extremely limited. We wish you to consider this fact in examining the map below. This map shows the location of a new almond tract which our association has recently acquired, and which is now being divided into 10-acre units.

According to Mr. G. A. Nehrhod, our Field Manager, who is the acknowledged authority of the Pacific Coast, the Paso Robles district is the one ideal section of California for almond culture. Here, and here only, can almonds be successfully grown without irrigating. Nor is fertilizing necessary. This is because of the peculiar formation of the soil, which is largely composed of what is known as sea marl adobe, highly impregnated with lime and potash, the very elements which almond trees must have to insure sturdy growth and prolific yield.

We Select Only the Cream of This Choice Almond Land

You must not think that all the land in the Paso Robles district is adapted to almond culture, nor that all sections are alike as to productivity. For instance, a prospective buyer of one of our almond orchard tracts wrote to a government official in charge of the Pacific District, Agricultural Section at Los Angeles, stating that our Association and our almond land holders. The first we know of it was when we saw a bulletin signed by this official, reading in part as follows:

Subject—Associated Almond Growers of Paso Robles

"This project has already received the endorsement of some of the leading horticulturists of California.

"The land purchased by this company includes some of the best almond producing land in America, and a purchaser from them will possess himself of land which will unquestionably produce successful crops of this type of nut.

"Concerning other lands in the locality which might benefit by the reflection of success gained in the holdings of the Association."

"The additional advice is given that, in the Paso Robles section, there are large acreages which carry upon their surface apparent opportunities in almond culture, but which, when brought to the test as to quality of soil, freedom from late Spring frosts and other questions necessary to success, can in no wise be termed favorable areas for almond culture."

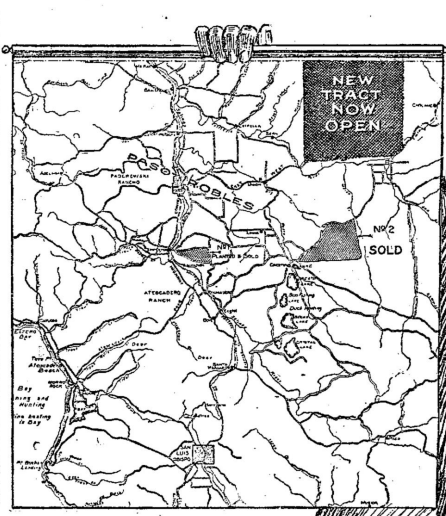
A copy of the complete Bulletin, signed by the Government official mentioned, will be mailed free on request.

Consider the note of warning sounded by the advice given "concerning other lands" which might benefit by reflection of success gained in the holdings of the Association."

Note also the additional advice regarding "large acreages which carry upon their surface apparent opportunities."

Soil Tested and Proved

Mr. Nehrhod takes no chances. He never relies upon surface indications, no matter how favorable they may appear. He selects all of the almond land for our Association, and under no circumstances will he give his O. K. to a tract until he has thoroughly tested the soil and is positively convinced that it has every qualification for successful almond culture. Notice the respective locations of the tracts already sold and planted and the New Tract recently opened. There are many thousands of acres separating these tracts, and a great deal of this land gives evidence of "surface opportunities" in almond culture. But tests covering large areas of this land prove that it does not measure up to the requirements which we demand in our almond lands.



\$2500 to \$3000 a Year for Life

FROM ONLY 10 ACRES

We tell you positively that if ever there was an opportunity for you to provide a sure and steady income as a protection against the uncertainties of the future—against the time when advanced years may find you outside the ranks of the money earners—this is that opportunity!

Why do you realize that within a few years after it is planted, one of these 10-acre almond orchards will NET you an income of from \$2500 to \$3000 a year FOR LIFE? This is a VERY CONSERVATIVE estimate.

According to Mr. Nehrhod's estimate, comparatively young almond trees,

How Your Interests Are Absolutely Safeguarded

The largest Trust Company on the Pacific Coast acts as custodian of the development fund created by the money sent to us by buyers and not a dollar of this fund can be used for any purpose except for orchard development—cultivating the ground, furnishing and planting the trees, weeding, harvesting, marketing. This Trust Company holds the title to the land and upon completion of your orchard will deliver to you the deed and title to your orchard.

Crops Pay Half

A moderate payment down and a larger one at the end of \$2500 a month puts you in possession of one of these big profit-making 10-acre orchards of 100 almond trees. But you pay only half the price out of your pocket. We will accept payment for the balance from the sale of the almonds after the trees are in bearing. We must see that the orchard "makes good" for you before we can fully pay. It is in our own interests to keep your property in the best possible condition.

Not a Crop Failure in 35 Years

Where trees have been properly located there has not been a crop failure for 35 years. The ideal soil and climatic conditions which prevail here, combined with the choice pedigreed trees we plant and the scientific care given them by our experts, explain why the crops are so heavy and of the very finest quality.

Our Money-Back Guarantee

If you can conveniently do so, by all means make a trip to Paso Robles and examine conditions there first hand. Investigate. If you do not find everything just as represented, we will refund to you any payment you have made, together with your railroad and Pullman fares. This same offer holds good if, instead of going yourself, you have a representative make the trip of investigation.

Associated Almond Growers of Paso Robles

MAIN OFFICE: G. H. ARNOLD, Special Representative, 1201 Plymouth Building, Minneapolis, Minn.



when properly planted in the right kind of soil and given scientific care in the early stages of their growth, may confidently be expected to bear 20 pounds of almonds a year. We plant and bring into bearing 700 of the finest pedigreed nursery grown almond trees to each 10-acre orchard. The conservative estimate, therefore, is 14,000 pounds from the 10 acres. We figure profits on a selling price of 25 cents per pound, the price paid to Paso Robles growers in 1918. Last fall (1919) the price ranged from 50c to 32 1/2c. Just figure for yourself what the profits actually are.

INVESTIGATE Come to Our Offices

1201 Plymouth Building. Open 9 a. m. to 6 p. m. Daily. Any evening by appointment, telephone Main 9114.

We want you to get all the facts about this wonderful investment opportunity so that you may intelligently decide as to whether or not it is one that you can conveniently go into.

So call at our office and get full particulars. Let us show you our magnificent collection of large colored photographs of the almond orchards at Paso Robles in all stages of development from the one-year-old up to the full bearing stage.

Let us explain fully our monthly payment plan which makes it so easy to own one of these big profit-making almond orchards. Let us even fully explain how completely our interests are safeguarded by the largest Trust Company on the Pacific Coast.

Come prepared to ask questions. We want to satisfy you fully in every particular before you even think of investing a dollar. Come any time that suits your convenience.

FREE ILLUSTRATED BOOK If you can't come to our office, send for this book. It is filled with pictures of the almond district and gives an exhaustive description of the growers at Paso Robles, and is of opportunity. Send the coupon and get a copy—FREE.



FREE BOOK COUPON—MAIL TODAY

Associated Almond Growers of Paso Robles, 1201 Plymouth Building, Minneapolis, Minn.

Without obligation on my part, send me your FREE BOOKLET. Tell me more about your Almond Orchards, price terms, etc.

Name _____ Address _____ City _____ State _____

Wm. E. 122

Figure 2. Advertisement for 1920s California almond investment scheme promising "No irrigating." Placed by the Associated Almond Growers of Paso Robles. Source: Minneapolis Morning Tribune (February 29, 1920, 9). Courtesy of the Minnesota Historical Society.

new ground for investment, and growers followed. In the 1940s, almond planting moved into the hotter, drier valleys that flood irrigation could now reach and rain-fed orchards struggled to compete (Riley 1948). In the 1950s, sprinkler systems brought sloping land into production, drawing orchards away from the frost-prone flats (Aron 1988). The decisive expansion came after 1970, when the state-funded Central Valley Project and California Water Project delivered northern river water to the valley at subsidized cost (Reisner 1993). Capital poured into new orchards and almond land quadrupled between 1970 and 1985 (Aron 1988). When micro-irrigation lowered water costs in the 1980s (Fereres et al. 1982), growers then pushed almonds into the Central Valley's hottest, driest southern counties (Schwankl and Prichard 2017), a trend that continued from 2000 to 2020, when almond farmland tripled. As production moved south into ever more arid ground, the water the industry deemed necessary climbed with it: The California Almond Board now recommends as much as 54 to 58 inches (1,370–1,470 mm) in the southern districts, against 44 inches (1,120 mm) in the north (Fulton, Norton, and Shilling 2019). It was figures like these—rendered as a water footprint of some 12,000 liters per kilogram, beside roughly 1,000 for wheat or maize and 300 for tomatoes—that would later make the almond a byword for agricultural excess (Arax 2018). Water's presumed abundance had been built into the crop itself.

The irrigated almond hydrosocial configuration is more than water infrastructure. The almond's drought-adapted biology was itself an obstacle that capital reengineered. One example is the widespread adoption of peach rootstock. The peach is a close cousin of the almond and the two remain cross-fertile, yet peach thrives in moister soil where almond's roots would drown or rot. Experiments with peach rootstock began at the University of California in the 1920s, but its use expanded in the 1950s (Day 1953) as state irrigation networks drew the almond southward into the nematode-infested soils of the San Joaquin Valley. Peach rootstock quickly became the industry norm. In addition to resisting nematodes, it supported vigorous tree growth and uniform crops; and peach seedlings were easy to propagate (Day 1953). What they lacked was the almond's deep taproot and capacity to exclude sodium and chloride from uptake into plant tissue (Doll et al.

2014). That absence would become consequential years later, when irrigation and chemical application increased salt concentrations in soil and groundwater.

The present-day California almond production ecosystem evolved in a landscape where plentiful water was effectively guaranteed. Water's presumed abundance has influenced everything from chemical regimes to pollination requirements to investor expectations (Sanden 2007; Waldman, Rangarajan, and Chediak 2023). Water infuses the gamut of almond management practices. Chemical fertilizer is delivered through irrigation. Water invites weeds, bacteria, fungus, and insects, prompting significant use of herbicides, fungicides, and pesticides—especially as trees are now typically left unpruned. The sheer number of almond flowers draws around two-thirds of the U.S. honeybee population for annual pollination (Reisman 2025). Regulating tree growth with water enables mechanized production by ensuring a uniform tree shape that accommodates harvesting equipment. Mechanization, in turn, enables the low labor costs that make the crop appealing to corporate investors, who have poured money into almonds since the 1980s (Aron 1988; Waldman, Rangarajan, and Chediak 2023).

Irrigation also shapes what almonds are like to eat, altering kernel form and chemistry. Water-stressed trees produce lighter kernels with higher concentrations of sugars and aromatic compounds, whose sizes are smaller and vary from tree to tree (García-Tejero et al. 2020). This matters commercially because prices for commodity almonds are graded to kernel size (USDA 1997). The large, mild, uniform kernel of an irrigated orchard and the variable nut with concentrated flavors from a dry orchard are different sensory objects. Within the commodity supply chain, the smaller and more variable rain-fed kernel is discounted as substandard. Yet, as we show in what follows, these same qualities find a different valuation in organic markets, which irrigated orchards cannot easily enter.

Optimizing the almond for water-intensive production locks orchards into this configuration, exposing them should the water run out. Peach roots are shallow and, unlike the almond's, poor at excluding the salts that irrigation and fertilization deposit (Doll et al. 2014). One might therefore expect the severe droughts of 2012 through 2016 and 2020 through 2022 to have crushed the industry, but

almond farmland increased significantly. With rivers and canals dry, growers underwrote expansion by mining groundwater, sinking thousands of new, ultra-deep wells into ancient aquifers (Hanak et al. 2019; Waldman, Rangarajan, and Chediak 2023). On existing orchards, that groundwater kept trees in production, even as the pumping drew decades of irrigation salts down into the aquifers those wells now tapped (Levy et al. 2021), delivering to the roots the salts they struggled to exclude. On the hundreds of thousands of hectares newly planted in these years, drought functioned as an investment opportunity. As drought slowed production, almond prices rose (Swegal 2017). Venture capital, pension funds, and wealthy corporate growers (like billionaire Stewart Resnick, who holds more than 30,000 hectares) drove a massive expansion, enabled by the state's once-lax groundwater regulation (Arax 2018).

Almond's expansion during drought did not go unnoticed. A wave of media coverage denounced almonds as a thirsty crop. Some labeled almond milk consumers "ignorant hipsters" whose food choices exacerbated the state's water crisis (Philpott 2014). Others highlighted corporate enclosures of water, decrying the perverse market logic of a crop boom unfolding amid drought (Gumbel 2015). This scrutiny prompted public demands that California's almond sector answer for its water use (Reisman 2019). The industry countered with a narrative of efficiency. It noted that peach, apple, and walnut have similar water footprints; that the state's beef and dairy farms use far more; and that almonds are a climate-friendly plant-based protein (ABC 2023). The California Almond Board emphasized that 80 percent of growers use micro-irrigation, a technology it credited with making almond production 30 percent more water-efficient over two decades (ABC 2015). This efficiency narrative circulated in news articles that recast almonds as a scapegoat (McGinty 2015), emphasizing their economic value and importance to feeding the nation (T. Walker 2015).

The industry's rebuttal sought to naturalize almond production in California. Of course, potential profit relative to other crops is what drew many to plant almonds through the drought, and the micro-irrigation technology that made this possible was endorsed for yield-maximization long before it was rebranded for water conservation. Since the 1980s, California agronomists have promoted micro-irrigation as a way to save money on inputs (Feres

et al. 1982). The Almond Board funded micro-irrigation research to lower production costs as the crop moved into the hotter, drier south (Schwankl and Prichard 2017). Studies showed dramatic yield gains, especially with "fertigation," where water doubles as a delivery vehicle for fertilizer (Sanden 2007). By cutting water cost, micro-irrigation made orchards viable in the arid southern San Joaquin Valley, where evapotranspiration rates and groundwater reliance are significantly higher (Taylor and Zilberman 2017; Fulton, Norton, and Shilling 2019). Efficiency, then, did not curb the almond's water use but underwrote its expansion into places where more water is required.

What the efficiency narrative most conceals is the regulatory vacuum in which this groundwater-dependent expansion proceeded. California passed the Sustainable Groundwater Management Act in 2014 but designed it to phase in slowly, with full implementation deferred until 2040. In the interim, the law has done little to discourage overdrafting (Méndez-Barrientos et al. 2020). Institutional investors have continued to pour money into almond farmland. In 2020, Canada's Public Sector Pension Investment Board purchased over 4,000 hectares of San Joaquin almonds for \$234 million and drilled six 1,000-foot wells (Waldman, Rangarajan, and Chediak 2023), a single instance of the broader pattern by which scarcity rewards those with capital to reach ever deeper (Philpott 2021; Sorvino 2022). Meanwhile, smaller producers struggle to access the groundwater they depend on, even with the help of agencies intended to secure their water rights (Méndez-Barrientos et al. 2020). The costs are cumulative: Aquifer mining has degraded water quality, driven land subsidence, and curtailed water storage capacity across the Central Valley (Smith et al. 2017; Hanak et al. 2019).

In little more than a century, then, the almond was remade from a tough tree into an infamous thirsty crop. With that turnabout arose a hydrosocial territory of intensive production, woven from plant breeding, corporate marketing, subsidized water infrastructure, irrigation technology, farmland financialization, and agronomic authority. Coded within the seemingly benign quantification of the almond's water requirements is a mandate for extraction, one the sector has continued to obey, expanding through drought and public censure alike even as the aquifers beneath it decline and the orchards of those without

groundwater access die (Newman 2021). This hydro-social configuration did not remain fixed in California. It traveled.

California's Long Shadow: Irrigated Almonds in Spain

As in other Mediterranean countries, almond culture [in Spain] has been strongly—and adversely—influenced by the traditional belief that almond trees will yield a return from a piece of land, however poor or dry it may be, which would produce hardly any other crop.

—Harry Bryan, USDA Foreign Agricultural Service (1965, 9)

“Companies like us are the most important producers,” the agronomist said as we surveyed the 1,000-hectare almond operation he manages in Aragon, Spain. “We are proof that their varieties can be produced at scale,” he added, discussing the symbiotic relationship that his company has with a Spanish agricultural research center. The company operates like a tech startup, its business model built on mechanized production at scale. Their almond operation is orders of magnitude larger than the typical family orchard, its irrigated trees eight times more productive. High volumes let the company ship year-round and negotiate prices with the processors it depends on to shell its almonds. The self-consciously modern vision of agriculture displayed on its Web site and Instagram reel foregrounds regularity, order, and scale. The sales team notes how this aesthetic helps attract investors who might be hesitant about the vicissitudes of agriculture in a country known for water scarcity.

The operation is emblematic of the transformation taking place across Spain. The agronomist explained that a modern almond plantation is a mechanized plantation, and the most vital element of mechanization is water. Their water flows from a European Union-funded water project planned for decades and finally completed. The company leases land from retired cereal producers, many of whom had dreamed of pursuing irrigated agriculture themselves and had advocated for the water project. They now lack the capital and the appetite for risk needed to invest in land preparation, tree planting, and water infrastructure, and their children have moved to cities for work. The company employs migrant laborers for planting, pruning, and harvesting. An

elaborate system of soil sensors allows the agronomist to monitor water and fertilizer needs from his urban office. On our drive from office to orchard, he explained how the company is contributing to the region's economic development.

Irrigated almond production on this model has spread across Spain over the past decade. Industry experts estimate that several dozen operations exceed 1,000 hectares, more than 100 times the average Spanish orchard. This influx is often backed by financial capital from outside the agrifood sector. An article in the newspaper *El País* likened it to the construction boom of the 2000s, noting that “investment funds have gotten into almonds as they got into housing” (Ansede 2019). The intensive almond model is also marketed downward in scale. Firms advertise services to install irrigated orchards on smaller plots, converting from lower value commodities. One agronomist described a phone ringing constantly with requests from clients, many of them urban professionals looking to invest in almonds on fifty or so hectares.

This marks a new chapter in Spain's long history with almonds. For hundreds of years, the crop has supported resource-poor producers in the country's most arid regions, providing resilience to yearly fluctuations in rainfall and commodity markets (Morey and Fornés 2021). Largely from small, rain-fed orchards, Spain led the world in almond production until the 1980s, when it was surpassed by California. As California's almond kingdom swelled, Spanish production languished. This began to change in 2014 when prices more than doubled, topping €8 per kg. Californian output kept climbing, sustained by groundwater, but demand was rising faster still (Swegal 2017). This gave Spain's almond industry the impetus to intensify production. High kernel prices beckoned with the chance of huge profit margins at farm level. Those with capital to deploy (prominent almond processors, water companies, construction firms, and wealthy landowners) suddenly had a clear motive to push for the sector's development and to invest in farm-level transformations.

Many industry actors described this as a welcome shift. A refrain during interviews was: “Why did intensification take so long?” Almond processors, plant breeders, agronomists, and government representatives all spoke of the pressing need to “modernize” to emulate and compete with California. Here, modernization does not merely

equate to economies of scale. It means producing almonds with uniform taste, shape, size, and texture to match the profile curated in California, which is vital to competing for the booming markets in Europe and Asia. Crucially, the consistent size, shape and mild taste that define the exportable almond are, in part, products of irrigation. Processors increasingly reject the smaller and variable kernels of rain-fed orchards or offer significantly less for them. To meet a market defined by the output of irrigated production, Spanish growers must adopt the water-delivery configuration that produces it. A demand articulated at the point of consumption reaches back to reconfigure how—and how much—water moves through the orchard. These practices dramatically reduce almond's drought tolerance and demand significant upfront capital. Yet they ensure that orchards rival those in California for yield and consistency.

The modernization of Spain's almond sector has brought rapid and uneven results. National production has doubled over the past decade and that growth is almost entirely attributable to irrigation. Between 2009 and 2024, rain-fed almond area grew by only 15 percent whereas irrigated area increased nearly fourfold (from 41,000 to 159,000 hectares), raising its share of national almond area from 7 percent to 21 percent (Figure 3). This expansion is concentrated inland, in Andalusia, Extremadura, Aragón, and Castilla-La Mancha, where surface

water and groundwater are available but scorching summers drive high water demand. Irrigated area in Andalusia and Aragón grew fivefold, and in Extremadura more than thirtyfold. In the traditional Mediterranean regions, by contrast, rain-fed acreage has contracted sharply—by 42 percent in Catalonia and 31 percent in the Valencian Community—as older orchards are abandoned or converted. By our calculation from Spanish government data (Ministerio de Agricultura, Pesca y Alimentación [MAPA] 2010–2025), irrigated orchards occupied a fifth of Spain's productive almond area in 2024 but produced close to three-fifths of its almonds, having become the majority of national production in 2023. Industry respondents explained that this rapid intensification was enabled by the model established in California (see also Reisman 2025).

The economic promise of the California hydrosocial configuration looms large over this transformation—which some have called Spain's "almond revolution" (Ansele 2019). Industry actors often spoke about California with awe and reverence. Imaginaries of its scale, efficiency, yields, mechanization, and profits saturate corporate and industrial spaces. Offices are adorned with photos of California orchards, posters detailing California almond varieties, and maps of its production regions. Images of the Central Valley's expansive fields of blooming almond trees populate Web sites and presentations. Yet, the California almond ideal travels through

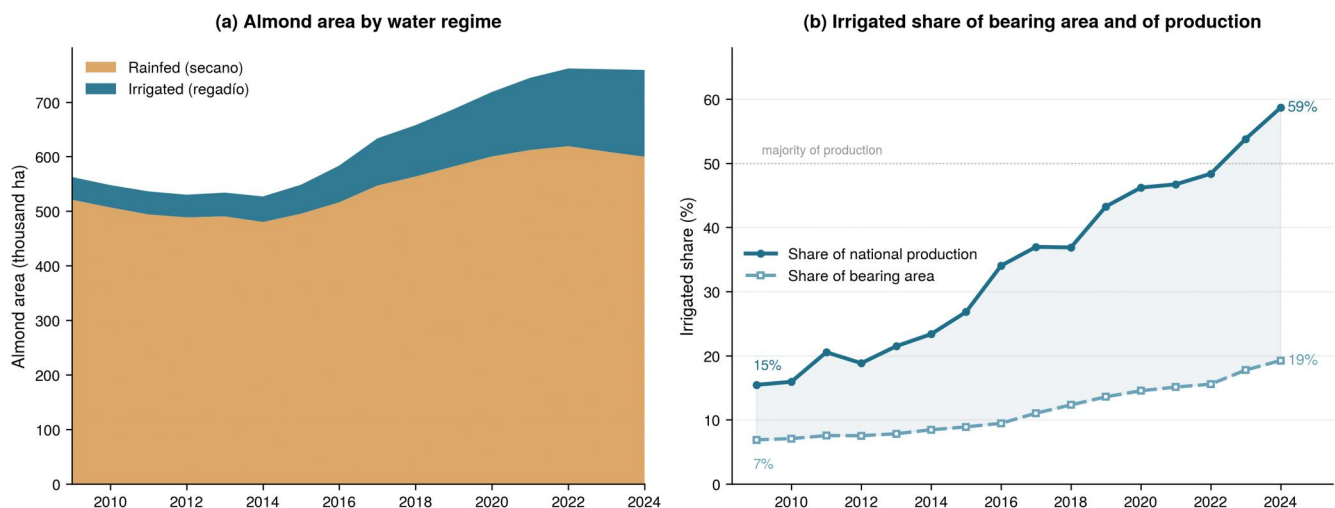


Figure 3. Expansion of irrigated almond production in Spain, 2009 to 2024. (A) Almond area by water regime. (B) Irrigated share of bearing area compared with irrigated share of national production. *Source:* Spain's Ministry of Agriculture, Fisheries and Food (MAPA) *Encuesta sobre Superficies y Rendimientos de Cultivos* [Survey of crop areas and yields]; (B) is from the authors' calculation from bearing-area and yield data.

more than imagery. A dense infrastructure of transmission has transposed the irrigated hydrosocial configuration to Spain. Industry knowledge and technologies, much of it developed with the University of California, have reached Spain through consultancies, partnerships, and professional associations. Growers, processors, and agronomists discussed field visits to California, and Spain's intensive operations serve as conduits for this expertise. At events such as the 2026 International Society for Horticultural Science Symposium on Almonds and Pistachios, the boundary between agronomic science and agribusiness can be difficult to locate. Presentations addressed how to optimize orchards for irrigation-intensive systems—rootstocks, canopy architecture, chemical regimes, irrigation scheduling—and virtually none examined rain-fed dynamics. The field excursions centered on intensive corporate plantations using proprietary rootstock. The technoscience of intensive irrigation circulated less as one option among others than as the horizon within which almond science is done.

The irrigated configuration thus reproduces itself not only through capital and infrastructure but through the conditions under which agronomic knowledge and almond varieties are developed. Spain's public agricultural research once addressed smallholder almond producers' resilience, developing late-flowering, self-pollinating varieties for dryland conditions. As state funding eroded, industry partnerships became essential to sustaining research programs and the range of researchable questions increasingly reflects the demands of agribusiness. This shift is evident in the trial fields themselves, which are often irrigated (in part to accelerate the breeding cycle, as watered trees mature faster), with varieties grafted onto vigorous hybrid peach–almond rootstock. Selection proceeds on traits that register under abundant water, and the capacities that matter in dryland orchards, such as drought tolerance, leave no trace in the data. As detailed at the beginning of this section, intensive corporate plantations now serve as research and demonstration sites in their own right. Rain-fed systems do not lose the argument but cease to constitute a question.

What is not asked for is not bred for, and the consequences are inscribed in the almond plant itself. The Centro de Edafología y Biología Aplicada del Segura (CEBAS-CSIC), long devoted to the hard-shelled cultivars suited to Mediterranean

conditions, recently released two paper-shell varieties, Alaska and Florida, designed to emulate Nonpareil for intensive systems in Spain and beyond. In selecting against the hard shell that protects kernels from pests with minimal chemical intervention, these varieties signal a reorientation of Spanish almond genetics toward an export standard set in California, and toward the water and chemical regimes that standard presumes. Cultivars persist for decades. Spanish orchards could be built from this material long after the arrangements that produced it have moved on.

The Persistence of the Rain-Fed Hydrosocial Configuration

Asked why not focus resources on cultivars or rootstock for the unique challenges of dryland Spain, one plant scientist replied simply that rain-fed almonds “have no future.” Yet this view is not universal. Some Spanish researchers validate the continued importance of rain-fed almonds and elements of their research programs reflect this. Unlike in California, rain-fed almonds remain far from obsolete in Spain. Across the drylands where almonds have grown for centuries, a rain-fed hydrosocial configuration persists on some 600,000 hectares, organized by its own vernacular water logic and sustained by different markets. We examine this persistence here.

Rain-fed almond systems are designed to reduce risk while making do with scarce resources. Terracing and planting along contour lines are the most visible strategies of water capture and retention, both slowing runoff to increase the water absorbed in a particular patch of soil. Some producers claimed that these can double the water trees receive compared to regional rainfall data. Tree spacing works similarly, the number planted per hectare falling as rainfall declines. Frequent tillage is considered vital in the most arid lands. Producers described the way that a shallow plow breaks the soil surface to interrupt capillary evaporation as “like giving water to the soil.” Although less visible, the choice of rootstock is equally important. Directly seeded almonds generate deep taproots that can withstand drought far better than the peach–almond hybrid rootstock promoted by agronomists to raise yields. These technologies of water capture and retention are the rain-fed counterpart to the irrigated configuration's technologies of water control and delivery.

Lacking abundant quantitative data, this uncoded, place-based knowledge nevertheless represents an alternative mode of seeing water—one that is rendered illegible by efficiency accounting (Lankford et al. 2020).

Rain-fed producers across Spain described these practices as quintessential to the almond's resilience, and framed high productivity itself as a hazard. Optimizing for yield means increasing vegetative growth at the expense of roots, raising plant stress while reducing drought tolerance. Intensive systems carry fixed costs and risks that many find unappealing. Not only can water allotments be cut by the state during drought, but intensive orchards demand expensive fertilizer, pesticides, and frequent replanting. Several respondents declared that they would not install irrigated systems even if they could access the water. A low but reliable return beats higher yields shadowed by the risk of catastrophic loss. Many cultivate trees planted by parents or grandparents, and note that orchards yield more than a marketable crop: firewood, fodder for livestock, and a sense of place. Success with rain-fed almonds has historically been measured differently: not by accumulation but by reliability.

Yet the rain-fed configuration is under pressure. Producers emphasized how the sector's modernization destabilizes small farms already weakened by decades of waning state support and unable to compete with California in volume or consistency. Processors' rejection of their kernels, as we noted, is justified by size and taste standards set elsewhere. That California almonds often fetch a higher price in Spanish markets is a particularly sore subject. Many rain-fed producers have responded by positioning themselves to the market for organic almonds, which California producers cannot easily enter.

Organic certification offers a premium and a point of differentiation for Spanish producers because the irrigated configuration forecloses it in California. Water stimulates vegetative growth. The dense canopy and moist ground of an irrigated orchard create habitat for weeds, pests, and fungus, managed with herbicides, pesticides, and fungicides. Unlike the thick, hard shells of Spanish almonds, Nonpareil's paper-thin shell leaves kernels especially vulnerable. Before replanting orchards every twenty-five years, the soil itself is fumigated against almond replant disease. The high upfront costs of establishing irrigated plantations—including groundwater extraction

and land values pegged to the yields of high-producing trees—make conversion still less attractive. The result is a striking gap: Whereas 7.5 percent of California farmland is certified organic, only 2.0 percent of the state's almond land is certified (California Department of Food and Agriculture 2024).

Most of the world's organic almonds therefore come from rain-fed systems, predominantly from Spain, where 31 percent (more than 234,000 hectares) of almond land is certified (MAPA 2024). Many of these orchards were organic by default. The hard shells of Spanish almonds provide biophysical resistance to pests and fungus while uncertain rain-fall discourages investment in labor and inputs. Organic certification thus often codifies a practice that water scarcity had already imposed. Because organic almonds are scarce, they command a substantial premium (historically around two euros per kilogram above conventional), which flows to growers whose orchards the industrial configuration regards as deficient. The traits that mark these systems as backward by the standards of intensive production—low yields, minimal inputs, no irrigation—are what qualify them for a market that irrigated orchards, for all their productivity, struggle to enter. This is not to romanticize organic certification as a lucrative venture for clever smallholders. Speaking about the immense challenges of competing with irrigated almonds in both California and Spain, one almond processor in a rain-fed region emphasized that “organic certification is not just one path for rain-fed farmers to remain viable, it is the only path.”

Seeing Food as Hydrosocial

The story of almonds in California and Spain shows how quantitative accounts of food's water use can conceal the material, historical, and geographical processes through which water and food constitute one another. A hydrosocial lens uncovers how water needs are coproduced, situating agronomic practice and water metrics in place and time. Here we synthesize three insights from the preceding narrative. First, a food's water needs are not predetermined biologically but are expressions of the hydrosocial configurations in which it is enrolled—configurations built and maintained at considerable effort. Second, agricultural sustainability schemes

hinging on efficient water use can exacerbate the vulnerabilities they promise to resolve. Third, hydrosocial logics travel through food, territorializing new landscapes and generating uneven outcomes.

Tough Tree or Thirsty Crop?

How much water does it take to produce an almond? Within a configuration combining state-subsidized hydroengineering, yield-maximizing agronomy, a corporate food culture demanding consistency, permissive water law, and investor appetite for rapid returns, almond orchards use more than 1,400 mm of water per year. Yet almond trees sustain low-input, high-agrobiodiversity production on poor soils in regions without irrigation, tolerating as little as 200 mm of annual rainfall. Here the almond offers resilience to climatic and economic shocks in place of maximal profit and speculation. This unsettles the widespread diagnosis that almonds are inherently water intensive (Granco et al. 2023), a logic now frequently and problematically (Dickson and Clay 2024) extended to foods like avocados, milk, and cheese to render them categorically unsustainable. Depending on the configuration in which it is enrolled, the almond can be a tough tree or a thirsty crop. This suggests the need to rigorously examine other foods that have been flagged as resource intensive based on assessments of industrial systems alone.

It might be objected that the irrigated almond simply needs more water because it yields more. But that yield gap is itself a product of the configuration and it reflects more than just the quantity of water applied. In California, the system built around irrigation also entails intensive chemical regimes, unprecedented pollination support, and groundwater extraction during drought. Even the trees are fundamentally different organisms. Although the kernel is botanically the same, irrigation-intensive almonds grow on peach or plum roots that are adapted to abundant water, struggling with drought and the salts that build up after years of irrigation alongside chemical fertilizers—a stark contrast to rain-fed systems that make use of the almond’s deep taproot, which evolved in water-scarce environments. The California almond industry’s ongoing effort to engineer salt-tolerant rootstock (Sandhu et al. 2020) exemplifies how grafting and irrigation temporarily

resolved the “problem” of low, inconsistent yields while generating subsequent crises (cf. Guthman 2019) of salt sensitivity and irrigation dependence.

Almonds thus illustrate how the same food can be enrolled in qualitatively different ways of navigating the scarcity of water or its illusory abundance. Our analysis converges here with Reisman’s (2025) assertion that almond water requirements are “less a function of flows through plant tissues than flows of capital” (72). We extend this insight by situating that agronomic knowledge within the wider hydrosocial configurations that reengineered the almond tree alongside the supply chains through which its output circulates. Earlier we showed how almond water metrics describe a configured organism—one that the numbers helped produce—while presenting themselves as describing a species. This builds on hydrosocial scholarship (Swyngedouw 2009; Linton and Budds 2014) by showing that water and society remake one another not only through built infrastructure but through agronomic science and the bodies of plants themselves: rootstock substituted across species, varieties bred for irrigation, and shells thinned to suit processing. The uniform Nonpareil kernel is itself a hydrosocial product, its chemistry and appearance conditioned by the configuration in which it grows.

Efficient Extraction

Tracing almond intensification in California and Spain gives historical and geographical specificity to arguments on the limits of equating sustainability with efficiency (Lankford et al. 2020; Molle, Lankford, and Lave 2024). It reveals how metrics that quantify a food’s water use in the name of sustainability are artifacts of the production systems they measure. They do political work, reflecting dominant paradigms even as they shape food–water relations. The water footprint is exemplary here. Its broad acceptance as a sustainability metric let the California sector naturalize high water use by comparison to meat and dairy, a framing prominent in marketing plant-based proteins like almond milk (Clay et al. 2020). We argue that such metrics can entrench the water use they purport to discipline, echoing cautions that water saved through “efficient” technologies does not always return to the environment or nonindustry users (Boelens and Vos 2012; Lankford et al. 2020; Anderson and Cantor 2024).

The California almond industry's championing of micro-irrigation depended on the scale at which efficiency was measured: gains at the level of the plant, losses at the level of the basin. The almond case shows the Jevons Paradox in irrigated agriculture—efficiency gains lowering costs and thereby increasing overall use (Sears et al. 2018)—unfolding spatially as the technologies and discourses of efficient water use underwrote almond's expansion into hotter, drier places where per-hectare requirements are greater and access to surface water lower, even in a good year. Water “saved” did not return to the basin or to other users but was appropriated to extend production (see also Lankford et al. 2020). Micro-irrigation carries a further hydrological irony: It reduces the seepage that once provided incidental aquifer recharge under flood irrigation. Facing regulatory mandates to stabilize aquifers, the California almond industry is now retrofitting its landscape with Agricultural Managed Aquifer Recharge (Ag-MAR), deliberately flooding orchards in the winter. What was previously pathologized as inefficient water loss is now urgently being engineered back into the system.

The irrigated configuration foreclosed drought adaptation as well. Historically, the San Joaquin Valley absorbed dry years by fallowing. Cotton and other annual crops could be left unplanted through drought. As almonds expanded across the valley—accelerating, paradoxically, through the drought years—that flexibility was lost. Because they represent investments maturing over decades, permanent tree crops cannot be fallowed, locking in long-term reliance on groundwater (Hanak et al. 2019). Groundwater extraction was not so much chosen as structurally mandated by a cropping pattern that consolidated during, and despite, water scarcity.

Whether efficiency restrains or intensifies water use, then, depends less on the technology than on the configuration in which it operates. A key question is whether groundwater offers an escape from restraint, as it did in California for those who can afford it. There is a deeper problem with efficiency as a remedy, though. Efficiency presupposes a system that can be run on less. Yet the Californian orchard has been assembled so that sustained contraction is neither economically nor biologically survivable: rootstock unable to exclude the salts that irrigation deposits, almond prices tied to nut sizes that would be reduced under deficit irrigation, land valued

against those yields and water availability, and capital committed on that basis. Each element makes sense within the configuration and forecloses departure from it. That foreclosure extends beyond water. The same configuration resists conversion to organic even as that market grows faster than conventional. What looks like a technical inefficiency to be optimized is in fact a dependency that has been built, and that the configuration must continue feeding water to sustain.

Almond Hydrosocial Territorialization

Viewing food as hydrosocial helps illuminate the historical-geographical processes that produce viable farming regions. As the irrigated almond's hydrosocial territory developed and then globalized, it generated uneven outcomes. Shifts in Californian almond–water relations—from rain-fed systems through waves of irrigation technology to deep groundwater extraction—rendered new locations viable while making once-thriving farms unprofitable. The recent droughts exposed this winner-take-all intensification. In the San Joaquin Valley, overdrafting deep aquifers for almonds siphons water from shallower wells serving small farms and nonfarming residents (Sorvino 2022) and micro-irrigation prevents incidental aquifer recharge. In Fairmead, a predominantly low-income, Black community, hundreds of domestic wells ran dry (Romero 2015). This pattern extends beyond the almond frontier. In Oregon's Deschutes Basin, efficiency projects that piped canals to eliminate leakage similarly halted the incidental recharge sustaining shallow domestic wells (Anderson and Cantor 2024).

Almond cultivation has involved parallel water enclosures and social shifts in Spain. A significant share of national production now comes from a small number of massive, capital-backed irrigated orchards. This is the most visible form of hydrosocial territorialization, where a configuration of capital, industry demands, agronomic knowledge, and technologies that matured in California is grafted onto Spanish ground. Hydrosocial territorialization also proceeds more subtly, though. Seeking higher returns or simply to meet the new standards, many rain-fed producers have replanted orchards with laboratory-bred cultivars on peach–almond hybrid rootstock. These materials were developed where water was assumed. Peach rootstock succeeded in California because

irrigation rendered the almond's deep taproot unnecessary. Transplanted into Spanish drylands, it lacks the trait that made rain-fed cultivation viable. Recent droughts exposed the consequence: Rain-fed orchards on shallow-rooted stock fared poorly where traditional plantings endured.

Together the two cases reveal hydrosocial territorialization as a mobile process rather than a bounded outcome. It operates here through the almond itself, a commodity whose rootstocks, taste profiles, and knowledge practices encode the configuration that produced them—extending precarity to rain-fed producers whose practices are rendered backward and unmarketable. This adds to work on hydrosocial territories (Alba et al. 2025) by showing that configurations travel not only through capital and infrastructure but through biological material, arriving in places unable to supply the conditions they presuppose. Attending to food's hydrosocial life thus reveals a geography of uneven development that local water politics alone cannot explain.

Geographies of Food–Water Relations

This article traced the almond's intensification as a hydrosocial process, showing how power operates through the food–water interface to produce social-ecological precarity as well as openings for resistance. The three insights developed here share a premise: that the water a food requires, the places where it can profitably grow, and the growers who count as viable are not given in advance but made, through configurations of knowledge, technology, and capital that must be built and maintained. Approaching food–water relations this way—rather than isolating agriculture, irrigation infrastructure, or water policy as separate analytical objects—offers a way to bridge subfields that have developed largely apart. There is more to trace, including how food's hydrosocial life extends into labor relations, development policy, and climate adaptation; and how other metrics, technologies, and policies stabilize or disrupt the configurations they measure.

As climate change intensifies, techno-optimist promises of resilience through irrigation circulate alongside dystopian visions of water scarcity igniting conflict, both shaping public discourse, state policies, and the terms of corporate accountability (Meehan et al. 2023). The almond case cuts against both. It

shows irrigation as neither salvation nor catastrophe but a historically constituted, place-based practice—one that has made some landscapes productive while rendering others obsolete, and whose apparent necessity was manufactured by the configuration that produced it. Recognizing this does not resolve the question of how much water a food should use. It changes the question, from what a food requires to what arrangements have made it require that much, and whose interests those arrangements serve.

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Author contributions

CRedit: **Nathan Clay**: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing; **Jamie Lorimer**: Conceptualization, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing.

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Notes

1. As two examples, neither the framework's agenda-setting piece (Linton and Budds 2014) nor a recent review (Liao and Schmidt 2023) develops food or agriculture as an analytic object, mentioning them only in passing.
2. For example, a recent agenda-setting review (Yap 2023) and food geography textbook (Kneafsey et al. 2021) center land and territory among the field's material concerns without substantively engaging water.

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