

# Economic assessment of Chilean agricultural land use, labor demand and input requirements using the Delphi method. Part A: Fruits and nuts for fresh consumption

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## ABSTRACT

Fresh fruit production plays a central role in the agricultural sector of Chile, particularly under an export-led growth (ELG) model. This study aimed to examine the dynamics of Chilean fresh fruit production and market structure between 2017 and 2021, focusing on labor demand, agrochemical inputs, and export value evolution. Using a modified Delphi method, we estimated yield ranges and full-production area equivalents for key fruit crops, based on internal consumption, import/export volumes, and technical-economic standards. The real export value of fresh fruit increased by 24.4% over the study period, with cherries surpassing table grapes as the top exported crop, rising from US\$545.6 million to US\$1.80 billion. Export fruits accounted for 84.5% and 80.8% of national production in 2017 and 2021, yet 79.2% and 74.9% of total traded volumes, highlighting price differentials across international and domestic markets. Labor needs averaged 151-220 person-days ha<sup>-1</sup>, with extremes ranging from 40 (mechanized nuts) to 488 (strawberries), being estimated that between 40.4 and 94.5 man-equivalent jobs are generated per 1000 t fruit traded. Pesticide use ranged from 7.82 to 20.07 kg ha<sup>-1</sup> active ingredient, including copper-based compounds and dormancy-breaking agents, which significantly increase load in some crops. These values are within range of international benchmarks such as California and European fruit orchards. The results highlight the structural reliance on export markets and the high demand for labor, underscoring both the economic intensity and the environmental pressures of the fruit export sector in Chile.

**Key words:** Agrochemicals, Delphi method, fresh fruits, fruit export markets, fruit production, labor.

## INTRODUCTION

The growth of agriculture is a priority for governments given its impact on industrial and urban sectors, including the generation of foreign exchange, the development of value chains, and the reduction of poverty through improved access to food (Rosengrant et al., 2021). In emerging economies, characterized by higher poverty levels and lower technological development, agricultural growth acquires relevance. In this context, the export-led growth (ELG) model proposes that international trade can expand economic growth through agroexports, which act as an engine to stimulate the productive sector, attract investment, and generate employment, especially in rural areas (Seok and Moon, 2021). Furthermore, economic globalization has given international markets a pivotal role in food access, while free trade agreements have propelled the expansion of agroexport markets (Smith and Glauber, 2019).

Although the liberalization of international markets impacts labor markets, there exists scarce evidence regarding the relationship between agroexports and agricultural employment, especially when compared with

the more developed analysis in the industrial sector (Acemoglu et al., 2016). These effects vary according to the level of development of each country. In developed economies, such as the USA and other Organisation for Economic Co-operation and Development (OECD) members, only a weak positive relationship is observed between agricultural employment and agroexports, explained by the countereffect of agroimports and the sustained reduction of agricultural land (He, 2020; Seok and Moon, 2021), meanwhile, in emerging economies, agroexports and agricultural employment are central to economic development under the ELG model, given their potential to create jobs, raise rural incomes, and channel resources toward more competitive sectors (Kang, 2015). However, the development of the agroexport sector also produces negative externalities, particularly linked to pesticides use and the overfertilization of agricultural soils (Coria and Elgueta, 2022).

In Chile, the agri-food sector contributes 16.4% of total export value and reported an agricultural trade surplus exceeding US\$5 billion in 2017 (OECD-FAO, 2019). The sector also accounts for 9.3% of national employment and remains the main economic activity in many rural areas, mainly through agroindustry and the production of nuts and fruits for fresh consumption destined for exportation (Coria and Elgueta, 2022). Land dedicated to fruit orchards for international markets expanded from 194 947 ha in 1980 to 492 587 ha in 2020, often replacing land previously used by annual crops due to the higher profitability of fruit orchards with export potential (del Pozo et al., 2024).

The export-oriented fresh fruit sector is highly complex, given its broad diversity of species, wide range of production scales, and the number of territories involved. This complexity complicates the evaluation of the ELG model's impact. In agriculture, the modified Delphi method (Rittirong et al., 2024) has been proposed as an effective tool to integrate relevant indicators through successive consultation rounds with growers and experts, allowing the incorporation of individual perspectives into a shared consensus. The present study aims to examine the productive and market dynamics of the Chilean nuts and fresh fruits for export, building consensus, through the use of a modified Delphi methodology, on the productivity of irrigated land and its potential effects on agricultural employment, while also approximating the scale of negative externalities associated with pesticide use and fertilization.

## MATERIALS AND METHODS

### International trade assessment

To characterize the international trade of Chile in nuts and fresh fruits, public databases of exports and imports for the years 2017 and 2021 were used, including nominal prices in US dollars (USD) and traded quantities. Each harmonized code associated with these products was classified at the species level and according to the quality of the product as fresh and unprocessed.

For comparability, nominal prices for each year were converted into real prices with December 2024 as the base, incorporating the annual inflation reported by the Central Bank of Chile (2025) according to the linked series of the consumer price index (CPI) and an inflation deflator or correction factor ( $F_c$ ) (González et al., 2013). The correction factor ( $F_c$ ) was obtained through the mathematical expression  $[F_c = I_{2024}/I_{(i)}]$ , where  $I_{2024}$  corresponds to accumulated value of the CPI as of December 2024, and  $I_{(i)}$  is the accumulated value of the CPI for year  $I$ , with  $i = 2017$  and  $2021$ , respectively. The corrected prices in 2024 constant currency were then expressed in USD at the exchange rate in effect in December 2024, equivalent to 992.12 Chilean pesos (CLP) per dollar. Interquartile ranges and median values of nominal and real prices per metric tons (t) were estimated for each combination of transaction type, product category, and year.

### Assessment of the domestic market for nuts and fresh fruits

To complement the information on international trade, an assessment of the domestic market for nuts and fresh fruits was conducted using data from the Household Budget Survey (HBS) from 2017 and 2021 (INE, 2023), considering only the regional capital cities, which represent over 80% of the formal market and population. The average nominal price paid per kilogram per capita consumption and per capita expenditure were estimated for each category and year. Subsequently, as with international trade prices, nominal values were adjusted for inflation using the Central Bank of Chile (2025) through a  $F_c$  as of 31 December 2024 and then converted to USD at the exchange rate on 31 December 2024 of 992.12 CLP per USD.

### **Sources of information**

The collection of technical-economic information was carried out through successive consultation rounds with growers and experts using a modified Delphi methodology (Gibbon et al., 2007). This approach was selected to integrate empirical production data with expert judgment and to iteratively validate technical-economic parameters across heterogeneous production systems.

Initially, Chilean agricultural land was zoned based on georeferenced data from the Centro de Información de Recursos Naturales (CIREN) of the Ministry of Agriculture, including agroclimatic zoning, agricultural soil maps and the geopolitical organization of the territory. Based on this spatial framework, the main productive categories of nuts and fresh fruits, as well as technological levels, were identified within each zone to guide field data collection during 2022 and 2023.

For the purposes of this study, and following the guidelines of the VIII Agricultural Census of Chile 2020-2021 (INE, 2022), an Economic Productive Unit (EPU) was defined as a silvoagropecuarian production unit under unique management by a grower, with a cultivated area equal to or higher than 2 ha and/or registered agricultural sales during the previous year.

Within this framework, the modified Delphi process was implemented through three sequential consultation rounds, following the approach described by González et al. (2013) to construct technical-economic standards for nuts and fresh fruit production systems.

### **First Delphi consultation round**

The first round of structured open-ended questionnaires aimed at identifying the key components required to build technical-economic standards, including crops yields, pesticides and fertilizer use, tillage and cultural operations, labor requirements, and estimated workdays per hectare for both human labor and tractor use.

This questionnaire was applied to 46 Economic Production Units (EPUs) corresponding to nuts and fruit growers affiliated with extension and technology transfer groups from Instituto de Investigaciones Agropecuarias (INIA) (GETs) and private agricultural companies. The EPUs were stratified by productive category and edaphoclimatic zone, ensuring representation of the main nuts and fresh fruit production systems and agroecological conditions.

Responses were systematized and complemented with secondary technical information from the INIA institutional library, including sectorial interviews, technical bulletins, extension manuals, and crop management guidelines. Based on this combined information, reference technical-economic standards were constructed on a per-hectare basis, incorporating crop type and variety, technological level, orchard size, yields, and economic costs associated with labor, tractor use, pesticides and fertilizers.

### **Second Delphi consultation round**

In a second round, the preliminary standards were submitted for evaluation to a panel of 12 consultants and subject matter experts, forming a public-private expert group composed of professionals from Instituto de Desarrollo Agropecuario (INDAP) Technical Assistance Services (SAT), INDAP Local Development Programs (PRODESAL), Regional Ministerial Secretariats (SEREMI) and INIA.

Experts assessed the standards in terms of technical coherence, economic plausibility, and regional representativeness, providing qualitative feedback and quantitative adjustments. Revisions were incorporated iteratively, and convergence among expert opinions was used as a criterion for consensus, consistent with Delphi-based validation procedures.

### **Geographic coverage review and standards validation**

Geographic representativeness of the standards was subsequently reviewed by the National Irrigation Commission (CNR). This review identified gaps in territorial coverage, prompting additional targeted data collection in underrepresented zones. Finally, a third consultation round was conducted with an independent group of nut and fruit experts to confirm robustness, internal consistency, and applicability of the finalized technical-economic standards.

### Elaboration of technical-economic standards and data analysis

Reference technical-economic standards were developed for each factor combination by means of the software Serie EconoINIA MiniSoft Frutales (González et al., 2025). The software was employed to systematize primary and secondary information on labor requirements, tractor cultural operations, and fertilizers and pesticides used, and to standardize technical coefficients in order to compute per-hectare technical indicators across crops, technological levels and agroclimatic zones.

The resulting standards were organized in a structured database, establishing minimum-maximum ranges for yield, man-days per hectare (man-days ha<sup>-1</sup>), tractor-days per hectare (tractor-days ha<sup>-1</sup>), tons of fertilizers applied per hectare (t ha<sup>-1</sup>), and kilograms of active ingredient applied per hectare (kg ai ha<sup>-1</sup>). For fruit species with limited cultivated area, where empirical ranges could not be directly obtained through the modified Delphi process, a 5% confidence interval around expert-elicited reference values was applied.

Descriptive statistical analysis was used to summarize central tendencies and variability of the technical coefficients, supporting the construction of representative and internally consistent standards. To contextualize the results, the derived standards were compared with main fruit-producing regions under Mediterranean climates, including technical-economic studies from University of California (UC Davis), California Agricultural & Resource Economics Department (UC Davis, 2025) and agricultural studies from the Regional Government of Extremadura, Spain (Junta de Extremadura, 2022).

### Projection of full-yield area

To project the surface under full yield by species of nuts and fresh fruits per year, the projected domestic demand in tons for 2017 and 2021 was considered, together with exported quantities of nuts and fresh fruits for the corresponding year, minus the corresponding imports. Full-yield area was defined as the surface required to produce these quantities, using the yield ranges obtained from the modified Delphi methodology.

The projected full-yield surfaces were contrasted with data from VIII Agricultural Census of Chile (INE, 2022), to adjust the projections to a range of the most probable full-yield area for the period 2017-2021. This comparison allowed integration of international trade data with domestic consumption of nuts and fresh fruits and with census-reported surfaces.

Using the adjusted full-yield surface ranges and the reference technical-economic standards developed, probable annual labor requirements were projected, expressed as 260 work-days of 8 h per job. Similarly, tractor labor requirements were projected, expressed as 260 tractor-days of 8 h per job, based on the conversion of hours of use. Annual use of fertilizers and kilograms of active ingredients per hectare was also estimated according to the technical coefficients per species and area.

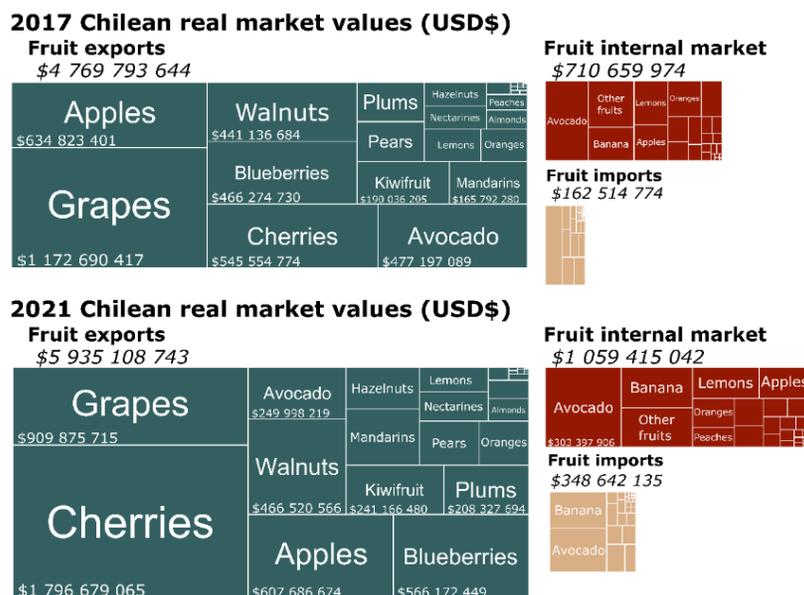
Within these ranges, elemental sulfur and horticultural oils were not included, as no maximum residue levels (MRLs) are established for these products, following Annex IV of Regulation (EC) N°396/2005 of the European Union (EFSA et al., 2023), despite their widespread use in high quantities. The impact of these variables on the sector's resilience is addressed in the Results and Discussion section.

## RESULTS AND DISCUSSION

For 2017, the Household Budget Survey of INE reported 66 894 transactions for fresh fruits and nuts, while in 2021 a total of 64 325 transactions were registered. These transactions were included in the analysis. Customs records reported 24 217 export transactions for fresh fruits and nuts in 2017, increasing slightly to 24 435 in 2021. Likewise, imports accounted for 938 transactions in 2017 and 1099 in 2021. These sets of transactions were also considered in the analysis.

For the years 2017 and 2021, it was determined that the total real value of exported nuts and fresh fruits, in USD December 2024, increased by 24.4% (Figure 1). In both years, exports of fresh fruits and nuts represented the main agricultural market, accounting for 84.5% and 80.8% of the combined production of nuts and fresh fruits in Chile, considering exports, projected internal demand and imports. These participation values are consistent with those reported by Pefaur (2022) for nuts and fresh fruits. Between 2017 and 2021, the real value of cherry exports surpassed that of table grapes, becoming the most exported fruit, with the main destination being China, as reported by Reyes (2022). In 2017, cherries export values accounted for US\$545 554 774 compared to US\$1 172 690 417 for table grapes, while in 2021, cherry exports reached a real value of

US\$1 796 679 065 and table grapes US\$909 875 715 (Figure 1). Other species that remained among the most exported fruits during this period were blueberries, apples and walnuts.

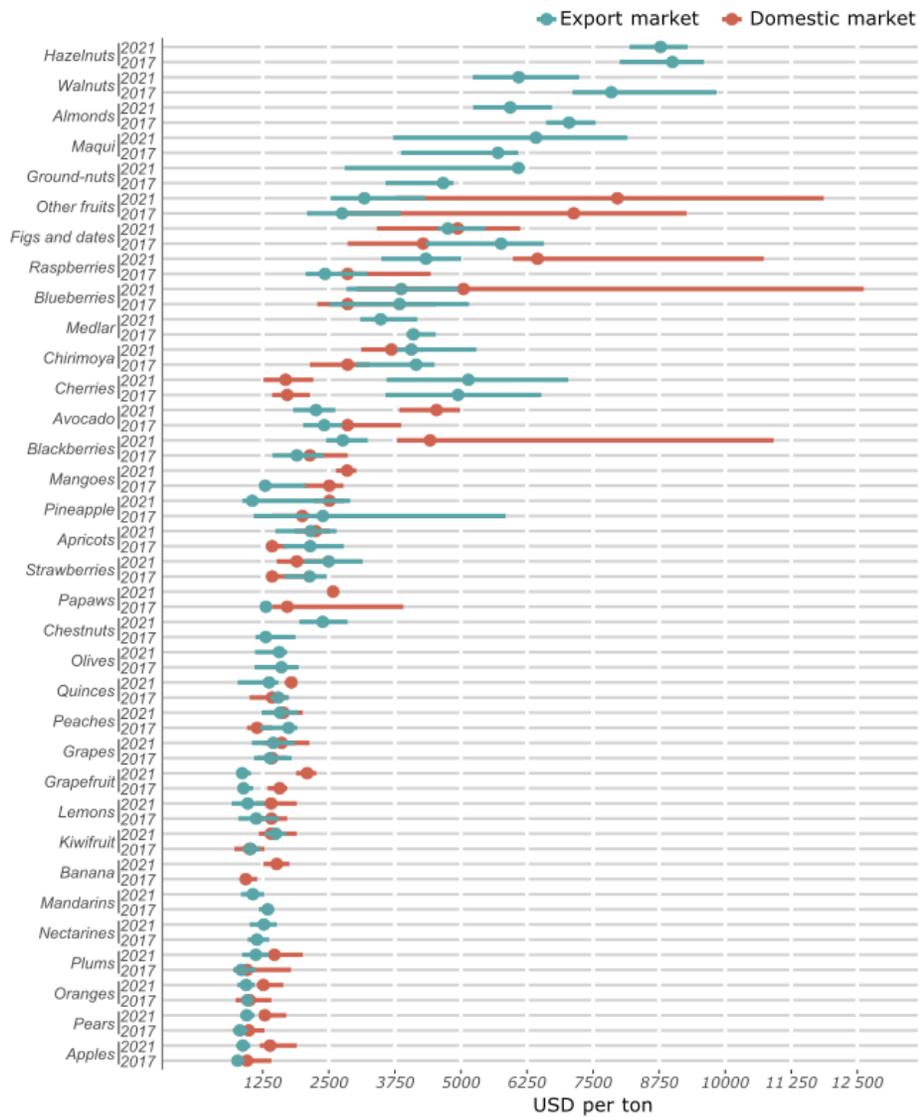


**Figure 1.** Real market value of Chilean fresh fruits and nuts trade by market type and year. Details are provided for the main agricultural sector, where 1 mm<sup>2</sup> equals US\$1 000 000. Monetary values are expressed to December 2024 at a rate of 992.12 CLP per USD.

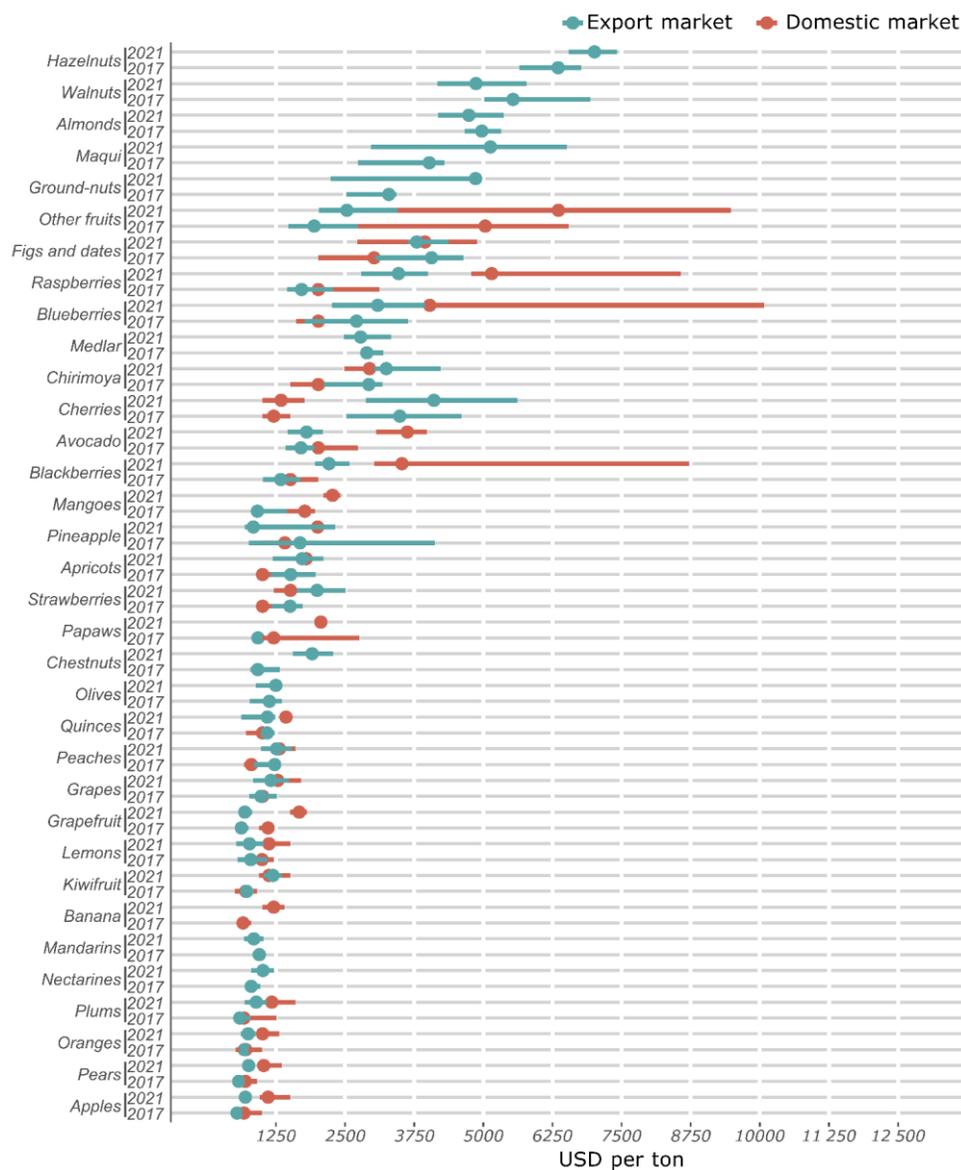
Within the export-led growth (ELG) model, Chilean fruits represent high economic value, through their relative importance among all produce is lower when analyzed by traded quantity. Nuts and fresh fruits for exports represented 79.2% and 74.9% of the total fruits traded in Chile in 2017 and 2021, respectively, explained by larger volumes traded at the domestic market at lower prices.

To characterize the differences in prices among nuts and fresh fruits in 2017 and 2021, real free-on-board (FOB) prices in USD t<sup>-1</sup> were analyzed alongside real household expenditure prices in USD kg<sup>-1</sup>, as reported in the Household Budget Survey (INE, 2023). For both nuts and fresh fruits, the medians and interquartile ranges (25%-75%) (Figure 2) showed consistency in ranking and price ranges between FOB values and household expenditures for the 2017-2021 period. This consistency aligns with the consultations made to the Delphi panel, who indicated that fruits for the domestic market generally corresponds to remnants of production originally destined for export.

Among the fruits with the highest real export value, such as cherries, blueberries and avocados, FOB real prices ranged between US\$2500 and US\$5000 per ton, with premium-quality cherries surpassing US\$5000, up to US\$7500 per ton (Figures 2 and 3). Apples stand out as an exception, since despite having the lowest prices per ton, they sustained a high share of agroexports in real value terms due to their large traded volume, evidencing its structural importance in the national fruit growing.



**Figure 2.** Median real prices comparison between export and domestic markets for Chilean fresh fruits and nuts products. Prices are adjusted to December 2024.



**Figure 3.** Median nominal prices comparison between export and domestic markets for Chilean fresh fruits and nuts products.

### Projected full-yield surface

The agricultural produce traded exhibits substantial variability in fruit quantities traded due to climatic conditions, price fluctuations, and market dynamics. Using yield ranges derived from the modified Delphi methodology for the main categories of nuts and fresh fruits, an equivalent full-yield area was projected (Table 1), defined as the surface required to supply exported and domestically consumed fresh fruits volumes, net of imports.

Comparison with the surveyed cultivated area for the 2020-2021 season (INE, 2022), indicates overall consistency within the projected ranges. However, pronounced divergences are observed in rapidly expanding fruit species, such as cherries, clementines and hazelnuts, where a substantial proportion of planted area corresponds to young, non-productive orchards. These discrepancies reflect a broader structural transformation of irrigated agricultural land in central-south Chile, characterized by the replacement of annual crops by high-value, export-oriented orchards, which continue to expand despite increasing constraints from water scarcity and urban sprawl, driven primarily by their relative profitability (del Pozo et al., 2024). In this

context, ranges of surface at full yield for the 2017-2021 period were projected, enabling an assessment of the growth dynamic and productive capacity of each fruit species.

**Table 1.** Estimated area in full-yield production by fresh fruit sector for pre- and post-pandemic scenarios. EPU: Economic productive unit.

Species	Yield	Chilean per capita acquisition		Full-yield estimated surface		Surveyed area	
		2017	2021	2017	2021	2021	EPU
	t ha <sup>-1</sup>	kg	kg	ha	ha	ha	
Cherries	5-30	0.27	0.49	10 403	41 050	60 672	4 666
Apples	20-80	3.24	3.26	28 915	26 321	29 259	6 554
Grapes	10-30	0.71	1.05	37 102	29 064	41 968	1 797
Avocado	5-30	3.03	4.26	28 019	16 190	30 663	3 064
Lemons	10-40	2.91	4.50	6 352	9 100	9 560	2 129
Walnuts	1-9	0.00	0.00	27 986	38 265	42 749	3 005
Plums	20-40	0.20	0.18	4 230	5 179	17 781	1 576
Blueberries	5-20	0.08	0.11	7 441	9 290		
Mandarins	20-40	0.00	0.00	4 147	6 870	10 541	453
Hazelnuts	1-4	0.00	0.00	3 252	6 859	34 817	705
Kiwifruit	15-30	0.45	0.39	6 879	5 879	5 973	346
Almonds	0-2	0.00	0.00	7 122	7 770	8 907	587
Pears	20-60	1.04	0.86	6 545	5 487	5 610	749
Oranges	15-50	3.12	2.76	5 816	6 324	6 063	962
Peaches	5-30	1.67	1.48	4 869	4 512	7 564	2 280
Nectarines	5-30	0.00	0.00	4 112	4 944	5 058	394
Strawberries	40-80	0.83	1.13	507	668		
Blackberries	5-15	0.02	0.01	118	59	1 210	1 468
Raspberries	10-20	0.04	0.03	92	52		
Apricots	5-30	0.05	0.05	76	75	539	450
Family orchard						4 314	16 311
Other fruits		1.96	1.93	7 439	6 909	7 846	4 286

### Labor requirements associated with nuts and fresh fruits

The production of nuts and fresh fruits represents a significant demand for labor in certain rural areas, characterized as seasonal due to the diversity of tasks required at each phenological stage and the agronomic management imposed by climatic conditions. This variability makes precise projections of workdays requirements challenging. Considering these factors, and based on the technical-economic standards for different fruit species, production levels and technology adoption, the modified Delphi methodology was applied to establish probable ranges of work-days ha<sup>-1</sup> and tractor-days ha<sup>-1</sup> for the 2017-2021 period (Table 2).

It was determined that the production of nuts and fresh fruits required a weighted average of 151 to 220 work-days ha<sup>-1</sup>, with a range that goes from 40 work-days ha<sup>-1</sup> in nuts with mechanical harvest to substantially higher values in orchards with extended manual harvests, such as strawberries. For strawberries, the Delphi panel reached a consensus on a requirement of 350 work-days ha<sup>-1</sup>, solely for harvest, and a total of 442 to 488 work-days ha<sup>-1</sup> for the full cycle. Similarly, in California, strawberry harvests have been reported to require between 208 and 555 work-days ha<sup>-1</sup> depending on yields, with a total of 286 to 633 work-days ha<sup>-1</sup> for the complete cycle (UC Davis, 2025).

As exemplified, harvest activities account for most of the variation in labor requirements among nuts and fresh fruits species. Harvest is predominantly manual in most fruits destined to exportation, to avoid bruising, with the exception of nuts, where it is mechanized. Plus, for export-oriented fruits, tasks such as supervising harvest, weighing, and fruit packing add an additional 57 to 75 work-day ha<sup>-1</sup> per season.

**Table 2.** Estimated agricultural labor and tractor use by fresh fruit sector products in full-yield production for the 2017-2021 period. In black the weighted average for fresh fruits and nuts.

Species	Surface range	Workforce		Machine labor units	
	2017-2021	man-day ha <sup>-1</sup>	jobs yr <sup>-1</sup>	tractor-day ha <sup>-1</sup>	tractor-jobs yr <sup>-1</sup>
<b>Fresh fruits</b>	<b>215 330-347 100</b>	<b>151-220</b>	<b>125 386-293 324</b>	<b>2.47-4.92</b>	<b>2 042-6574</b>
Cherries	41 050-60 650	177-373	27 946-87 009	1.44-4.50	227-1 050
Walnuts	28 000-42 750	40-115	4 308-18 909	2.62-7.62	282-1 253
Grapes	29 050-41 950	257-301	28 715-48 565	6.14-9.00	686-1 452
Hazelnuts	6 900-34 800	76-78	2 017-10 440	1.43-1.58	38-211
Avocado	16 200-30 650	137-155	8 536-18 272	0.99-2.59	62-305
Apples	26 300-29 250	220-293	22 254-32 963	3.03-3.59	306-404
Plums	4 230-17 750	40-190	651-12 971	2.41-7.06	39-482
Mandarins	4 150-10 550	162-191	2 586-7 750	2.09-2.31	33-94
Lemons	6 350-9 550	94-216	2 296-7 934	3.33-3.68	81-135
Blueberries	7 450-9 300	228-388	6 533-13 878	0.44-0.75	13-27
Almonds	7 100-8 900	75-82	2 048-2 807	1.44-12.50	39-428
Peaches	4 500-7 550	105-117	1 817-3 398	1.58-7.00	27-203
Oranges	5 800-6 300	185-196	4 127-4 749	2.09-2.31	47-56
Kiwifruit	5 850-6 900	187-257	4 208-6 820	2.41-2.78	54-74
Pears	5 550-6 550	220-293	4 696-7 381	3.12-8.59	67-216
Nectarines	4 100-5 050	105-117	1 656-2 273	2.45-6.00	39-117
Blackberries	50-1 750	251-393	48-2 645	0.48-0.53	0-4
Raspberries	50-1 250	239-400	46-1 923	0.50-0.94	0-5
Apricots	100-550	130-144	50-305	0.77-0.85	0-2
Strawberries	500-650	442-488	850-1 220	0.48-0.53	1-1
Family					
orchard	4 200-4 400	0-20	0-338	0-1.00	0-17
Other fruits	7 850-10 050	0-20	0-773	0-1.00	0-39

For cherries, as in the other fresh fruits species, harvest was identified as the most labor-intensive stage. Consensus from the panel indicated that 86 to 129 work-days ha<sup>-1</sup> of the total 177 to 373 work-days ha<sup>-1</sup>, required correspond to harvest, with expected yields of 12 to 15 t ha<sup>-1</sup>. These values are consistent with those reported in California, where cherry harvest requires about 80 work-days ha<sup>-1</sup>, for a yield of 12 t ha<sup>-1</sup> (UC Davis, 2025), and in Extremadura, Spain, where 56 to 65 work-days ha<sup>-1</sup> are associated with harvests yielding 8 to 9.5 t ha<sup>-1</sup> (Junta de Extremadura, 2022). For table grapes, consensus indicated 65 to 74 work-days ha<sup>-1</sup> for harvest out of a total of 257 to 301 work-days ha<sup>-1</sup>. These figures are comparable to reports from California, where 188 of 246 work-days ha<sup>-1</sup> correspond to harvest (UC Davis, 2025).

In this study, based on the full-yield surface projections for 2017 and 2021, and considering the 35 471 economic productive units (EPU) of nuts and fresh fruit growers surveyed nationwide in 2021, the sector was estimated to require between 125 386 and 293 324 man-equivalent jobs per year, accounting for all tasks required under full-yield conditions. In parallel, mechanized tasks demanded between 2042 and 6574 equivalent jobs per year, considering all practices required in productive fruit orchards, an estimate that does not account for the increase in labor requirements per ton of fruit typically associated with yield losses under adverse weather or droughts.

Under a climate change scenario, yield losses driven by the increasing occurrence of extreme weather events, such as late spring rainfall and summer heat waves, are likely to further reduce labor productivity and increase labor costs, as additional agronomic interventions (e.g., canopy management and fruit load adjustments) may be required to mitigate impacts on fruit size and total yield (Rezaei et al., 2023). Beyond management adjustments, the adoption of climate-resilient cultivars may partially offset yield losses while contributing to greater labor efficiency and employment stability in fruit production systems.

Based on estimates of 3 032 556 t fresh fruits produced for 2017 and 3 177 412 t for 2021, it is projected that between 40.4 and 94.5 man-equivalent jobs are generated per 1000 t of fruit traded, but having in consideration that labor is highly concentrated during the harvest season, resulting in a higher proportion of seasonal or part-time employment rather than full-year positions.

### Use of fertilizers and pesticide active ingredients

Following the same methodology applied for estimating employment and mechanization, approximate ranges of fertilizer use and pesticide active ingredients per hectare were calculated for each fruit crop considered (Table 3). This estimation seeks to quantify overall trends in fertilizer and agrochemical load in fruit species that export their production fresh, without replacing specialized methodologies for environmental sustainability assessment.

**Table 3.** Estimated use of fertilizers and pesticide active ingredients by fresh fruit sector in full-yield production for the 2017-2021 period. In black the weighted average for fresh fruits and nuts.

Species	Surface range 2017-2021		Fertilizers		Pesticides	
	2021	ha	t ha <sup>-1</sup>	t yr <sup>-1</sup>	kg ai ha <sup>-1</sup>	t ai yr <sup>-1</sup>
<b>Fresh fruits</b>	<b>215 330-347 100</b>		<b>0.52-0.69</b>	<b>432-921</b>	<b>7.82-20.07</b>	<b>6 478-26 796</b>
Cherries	41 050-60 650		0.57-0.65	90-152	7.19-23.90	1 135-5 575
Walnuts	28 000-42 750		0.31-0.68	33-112	8.65-45.10	932-7 415
Grapes	29 050-41 950		0.84-0.93	94-150	6.35-7.16	709-1 155
Hazelnuts	6 900-34 800		0.69-0.76	18-102	8.64-12.90	229-1 727
Avocado	16 200-30 650		0.58-0.65	36-77	4.96-5.48	309-646
Apples	26 300-29 250		0.46-0.76	47-86	11.00-37.30	1 113-4 196
Plums	4 230-17 750		0.54-0.80	9-55	14.80-19.20	241-1 311
Mandarins	4 150-10 550		0.91-1.01	15-41	6.86-7.58	109-308
Lemons	6 350-9 550		0.60-0.83	15-30	6.41-19.40	157-713
Blueberries	7 450-9 300		0.16-0.22	5-8	3.28-17.20	94-615
Almonds	7 100-8 900		0.52-0.57	14-20	12.90-13.30	352-455
Peaches	4 500-7 550		0.54-0.55	9-16	2.40-8.90	42-258
Oranges	5 800-6 300		0.91-1.01	20-24	1.01-7.22	23-175
Kiwifruit	5 850-6 900		0.55-0.62	12-16	36.50-39.00	821-1 035
Pears	5 550-6 550		0.25-0.50	5-13	3.26-6.63	70-167
Nectarines	4 100-5 050		0.52-0.58	8-11	8.77-8.90	138-173
Blackberries	50-1 750		0.16-0.22	0-1	3.28-24.80	1-167
Raspberries	50-1 250		0.16-0.22	0-1	8.15-17.20	2-83
Apricots	100-550		0.72-0.79	0-2	0.77-0.85	0-2
Strawberries	500-650		0.40-0.80	1-2	1.05-3.02	2-8
Family						
orchard	4 200-4 400		0-0.05	0-1	0-1.00	0-17
Other fruits	7 850-10 050		0-0.05	0-2	0-15.40	0-595

For fertilizers, a weighted average application of 0.52 to 0.69 t ha<sup>-1</sup> was determined, with an estimated annual range of 449 to 931 t ha<sup>-1</sup> fertilizer applied across the fruit sector. Using the modified Delphi method and complementary technical data, a high variability in reported application volumes was observed, along with differing technical criteria for their use, regardless of the fruit species evaluated. Only a tendency toward lower fertilization was found in fruits of lower commercial value and low varietal turnover, such as blackberries, peaches, and nectarines.

In agrochemicals, the technical-economic standards developed revealed wide variation depending on the presence or apparent risk of pests and diseases, as well as orchard management systems in organic transition or organic production (Table 3). The amounts of active ingredients applied per hectare of fresh fruits, according to the evaluated standards, ranged from 7.82 to 20.07 kg ai ha<sup>-1</sup>. These values are higher than those reported in Kuwait for all agricultural sectors between 2007 and 2015, with 4.5 to 12.8 kg ai ha<sup>-1</sup> (Jallow et al., 2017), but

remain within the ranges reported in the literature for different fruit species. For apples, for example, a survey of 2549 commercial orchards in Vienna reported an average of 56 kg ha<sup>-1</sup> pesticide use (Zaller et al., 2023). In California, recent studies show lower values in cherries (3.55 kg ai ha<sup>-1</sup>) and walnuts (2.71 kg ai ha<sup>-1</sup>), but higher levels in table grapes (21.63 kg ai ha<sup>-1</sup>) (UC Davis, 2025). Climate change has increasingly reshaped pesticide application patterns over recent decades, primarily due to higher frequency and intensity of crop pest and disease outbreaks. As warming trends and altered precipitation regimes continue, pesticide demand is projected to increase toward the end of the century (Wang et al., 2022). Overall, the amount of active ingredient applied per hectare varies across orchards and seasons, but the estimated ranges in this study reflect different combinations of application frequency and product rotation at recommended doses.

The main differences with agrochemical loads in California are explained primarily by two factors. First, the use of plant growth regulators to break winter dormancy, widely applied in certain species for early-season production targeting exports. Their application ranges from 15 to 45 L ha<sup>-1</sup> commercial product depending on species and spray volume, representing a load of 7.8 to 23.4 kg ai ha<sup>-1</sup>. Second, the use of copper compounds in the traditional preventive control of bacterial diseases recommended in Chilean phytosanitary programs, applied before flowering to avoid floral damage or fruit spotting (Lovera et al., 2025). These are used at 2 to 10 kg ha<sup>-1</sup> per application, with loads ranging from 1.74 to 8.7 kg ai ha<sup>-1</sup>, whereas in California strictly new-generation formulations are applied (UC Davis, 2025).

In this sense, at the regulatory level, the European Union has implemented maximum application limits per hectare for certain compounds to promote safer use. In the case of copper, a limit of 28 kg ai ha<sup>-1</sup> over a period of 7 yr, equivalent to an average use of 4 kg ai ha<sup>-1</sup> yr<sup>-1</sup>, was set to reduce potential soil accumulation and exposure of non-target organisms (EFSA, 2025). EFSA (2025) itself has indicated that applications of Cu-based agrochemicals do not significantly contribute to dietary Cu intake in the population. Another case of regulation concerns glyphosate, a widely used herbicide, whose application was restricted to a maximum of 3.6 kg, equivalent to 1.72 kg ai ha<sup>-1</sup> yr<sup>-1</sup> (Kudsk and Mathiassen, 2020).

## CONCLUSIONS

Chilean fruit production for fresh export has maintained a sustained growth dynamic, with traded volumes showing low fluctuation between 2017 and 2021. During this period, a structural change in the composition of exports was observed: Cherries displaced table grapes as the main exported fruit, reaching a real value of US\$1796 million in 2021, compared to US\$909 million for table grapes. At the same time, fresh fruit exports represented 79.2% of total fruit traded in 2017 and 74.9% in 2021, consolidating the central role of Chilean fruit production within the export-led growth model.

It is estimated that the sector requires between 125 386 and 293 324 annual full-time equivalent jobs to sustain a productive surface ranging from 215 330 to 347 100 ha, which in 2021 reported US\$5935 million in export returns. These results reflect the high dependence of agricultural employment on irrigated fruit production, while also revealing challenges linked to the intensive use of agrochemicals. The application of a modified Delphi approach enabled the derivation of realistic estimates of productivity and labor requirements, while also revealing trade-offs between economic growth, environmental sustainability, and employment stability. These findings open space for discussion on the future viability of Chile's export-led growth and the role of climate-resilient strategies in sustaining it.

### Author contribution

Conceptualization: A.D., J.G. Methodology: A.D., J.G. Software: A.D. Validation: A.D. Formal analysis: A.D. Investigation: A.D., J.G., J.O. Resources: A.D. Data curation: A.D. Writing-original draft: A.D., J.G. Writing-review & editing: J.G., J.O. Visualization: A.D. Supervision: J.G. Project administration: J.G., A.D. Funding acquisition: J.G. All co-authors reviewed the final version and approved the manuscript before submission.

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