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Optimization of Water and Land Allocation in Fruit Orchards over a 20-Year Period

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Abstract: This study proposes a nonlinear programming model for the optimization of water and land allocation in a 1000 ha orchard over a 20-year period to maximize farmers' net profits. Different scenarios were evaluated, including equitable and unrestricted land allocation, and the risks associated with fruit production were considered. Additionally, a sensitivity analysis that focused on the variability of labor and water availability was conducted. The results reveal that with equitable land allocations and no constraints on the cultivated area, cherry emerges as the most profitable crop, although there are large risks associated with its price volatility. The introduction of risk and land allocation constraints highlights the importance of crop diversification in mitigating economic risks. A sensitivity analysis indicated that reductions in water and labor availability significantly affect the optimal cropping pattern of an orchard, suggesting that the efficient and adaptive management of resources is required. The proposed optimal cropping pattern maintains the economic viability of the orchard even with 70% and 24% reductions in water and labor, respectively. This approach underscores the importance of implementing resilient and sustainable agricultural strategies to ensure food security and increase economic stability in the face of changing climatic and labor conditions.

Keywords: water resource management; crop patterns; sustainability; fruit production

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1. Introduction

Agriculture is the primary use for water worldwide, with an estimated 70% of freshwater used for crop irrigation [1,2]. This demand for water is expected to continue to rise due to increasing pressure to produce more food, which is the result of population growth and changing diets [3]. In fact, the world population is projected to reach 9 billion by 2050, which will lead to a significant increase in food production and water consumption [4], posing challenges to the sustainable use of water in agriculture, particularly in water-scarce regions where competition for water resources is high [5]. Agricultural production is fundamental to improving nutrition and serves as the main source of income for farmers, and it also plays a crucial role in food security, economic stability, and society [6].

Global fruit production has experienced a remarkable increase in recent decades [7] due to population growth, changing dietary preferences, and improved agricultural techniques [8,9]. On a global scale, the cultivated area fruit crops covered increased by 55% between 2000 and 2020, and fruit production reached 887 million tons in 2020, reflecting both the expansion of the sector and the use of new technologies and improved agricultural practices [10].

Currently, Chile has established itself as the leading producer and exporter of fruits in the Southern Hemisphere, dominating in the export of cherries, blueberries, table grapes, avocados, and walnuts to markets in North America, Asia, and Europe [11]. The O'Higgins Region stands out as one of the country's principal agricultural areas, contributing significantly to its fruit production and exports. However, in recent years, this region has been affected by a megadrought that has negatively impacted agricultural production. Additionally, the area devoted to fruit cultivation increased by 43% between 2003 and 2018, without proper planning, with a simultaneous decline seen in the availability of labor [12]. These challenges emphasize the need to develop management tools and strategies that enable the efficient and sustainable use of resources.

In this sense, optimization techniques, which are mathematical and computational methods used to find the best possible solution within a set of feasible alternatives [13], are being employed in water resource management to ensure food security as well as the availability and sustainability of water resources [14]. Determining optimal cropping patterns can improve water use efficiency, increase farmers' incomes, and help mitigate the adverse impacts of climate change and droughts [15]. Several studies have developed models that can maximize profits by determining optimal cropping patterns. For instance, Bhatia and Rana [16] used linear programming to determine optimal crop combinations, significantly increasing farm incomes. Chen et al. [17] developed a multi-objective programming model that combines an economic profit function and a water quality model to optimize cropping patterns under climate uncertainty, achieving a reduction in pollutant emissions without significantly affecting economic benefits. Richter et al. [18] reported a reduction of 28–57% in the use of water for irrigation by optimizing crop combinations while maintaining or improving the net revenues of agricultural land. Varade and Patel [19] applied particle swarm optimization (PSO) algorithms and teaching–learning-based optimization (TLBO) to determine optimal cropping patterns in areas with limited water resources, reporting increases in net profits and reductions in water use. Najafabadi and Ashktorab [20] developed a robust fractional linear programming model to determine sustainable cropping patterns, achieving a reduction in the use of inputs such as fertilizers and pesticides while maintaining profitability. Similarly, Abdi-Dehkordi et al. [21] developed a mathematical model to maximize profits and found that proper management and adequate cropping patterns can increase revenues, even with a reduced supply of and increased demand for water. Dariane et al. [22] proposed a method that could be used to determine optimal short-term cropping patterns in a four-reservoir system in the Karun Basin, Iran. Another study conducted by Varade and Patel [23] used advanced optimization algorithms, such as Jaya and PSO, to determine an optimal cropping pattern to maximize annual net returns, conserve groundwater resources, and achieve optimal land use in a region with scarce surface water resources and uncertain rainfall. Zeng et al. [24] developed a stochastic model in order to optimize water management in arid regions, using ecological and economic variables to promote sustainability in agricultural and ecological systems under conditions of high climatic variability and water scarcity. Zeng et al. [25] also proposed a hybrid stochastic–fuzzy model for planning irrigated agricultural production and forest protection in scenarios marked by water and land stress. This approach enables the generation of integrated strategies that maximize socioeconomic benefits while mitigating environmental impacts. Additionally, Kuschel-Otárola et al. [26] developed a multi-period optimization model to obtain an optimal cropping pattern for annual crops under different water availability conditions in order to generate monthly allocations of resources such as water, labor, and capital and maximize profits while considering the phenological stages of the crops. However, it is important to note that all these aforementioned studies are based on conceptual or theoretical models, which makes a direct evaluation and comparison of their proposed cropping patterns with real field results difficult. In fact, while these models can contribute to decision making in a significant way, they may not fully reflect the complexities of the agricultural sector.

Despite the numerous studies conducted on the optimization of cropping patterns, there are still significant gaps in the research on long-term land allocation, especially for extended periods of more than 15 years. Most of these studies focus on irrigation over a single season, which limits their applicability in long-term planning. To the best of our knowledge, no previous studies have proposed an optimal cropping pattern for fruit orchards while considering the volatility of fruit prices. Therefore, the main objective of this study is to develop a nonlinear programming model that optimizes land allocation for fruit orchards over a 20-year period and allocates water on an annual basis in order to maximize net profits in crop production. Our specific objectives are (1) to evaluate the impact of different fruit crop combinations on water use and crop productivity; (2) to analyze the risk associated with price volatility at the time of the orchard's establishment; and (3) to evaluate the impact of labor and water availability on orchard planning and management.

2. Materials and Methods

Given the current and potential challenges encountered during fruit production, a model was developed to optimize land and water allocation for different fruit crops. This approach seeks to maximize profits within different resource availability scenarios, thus serving as a tool for informed decision making. This model includes factors such as water availability and labor shortages, which are critical for sustainable fruit production. A 20-year planning period has been chosen based on several studies indicating that many fruit orchards can maintain optimal production levels during this period before facing challenges that compromise their productivity and economic viability [27–30]. Due to its theoretical nature, this model provides an approximate estimate of the yield using production functions. In this sense, the model evaluates how fluctuations in resource availability impact profitability and sustainability, determining optimal land and water allocations for each fruit crop based on economic returns and resource requirements.

2.1. Production Functions

An extensive bibliographic review was undertaken. Crop water production functions were obtained from studies or analyses carried out on field experiments conducted under different soil and climatic conditions and using different agricultural practices. Some of these functions were obtained from research conducted at the study site (described in Section 2.3), while others were obtained from different works on the topic. The analysis of the impact of the climate on fruit crop productivity focuses on real and potential evapotranspiration at the study site. This approach enables a more accurate estimation of the water available to plants and its relationship to the crop yield. To achieve this, a relative representation of yields and evapotranspiration with respect to the maximum potential of the fruit crop is used, making the comparison and parameterization of heterogeneous data more expeditious [31].

The crop water production function shows that there is a concave relationship between the water applied and the harvestable yield, leading to diminishing returns. This means that once the maximum production value is reached, any further increase in irrigation leads to lower yields [32,33]. The mathematical expressions that model these functions are commonly defined as follows [34,35]:

$$Y_{rel} = \alpha \cdot (ET_{rel})^2 + \beta \cdot ET_{rel} + \gamma \tag{1}$$

$$Y = \left[\alpha \cdot \left(\frac{ET_a}{ET_c} \right)^2 + \beta \cdot \left(\frac{ET_a}{ET_c} \right) + \gamma \right] \cdot Y_m \tag{2}$$

where α, β, and γ are empirical parameters obtained from the studies; Y_{rel} is the relative yield; ET_{rel} is the relative evapotranspiration; Y is the crop yield (t ha^{-1}); ETa is the actual evapotranspiration of the fruit crop (mm); ETc is the potential evapotranspiration of the fruit crop (mm); and Ym is the maximum yield of the fruit crop (t ha^{-1}).

2.2. Model Formulation

A nonlinear programming model has been developed, with a focus on optimal land allocation to maximize the net profits of fruit orchards over a 20-year period. This model takes a holistic approach that includes considering the proper management of water and land use, operating costs, and labor, as well as the risks associated with the volatility of sale prices. The key decision variables are land allocation and the annual allocation of water for each fruit crop.

This model adapts and extends the methodologies previously developed for annual crops by Carvallo et al. [31] and Kuschel-Otárola et al. [26] according to the specific conditions favored by the fruit crops evaluated.

2.2.1. Objective Function

The objective function is designed to maximize the total profits of the farm, which are calculated as the difference between sales revenues and the associated production costs. Revenue is calculated by multiplying the market price by the area and the crop yield, which is determined by the total amount of water applied. Production costs include direct costs such as labor, water use, and other agricultural inputs. The equation is represented as follows:

$$\max U = \sum_{i=1}^{n} \sum_{k=1}^{t} P_{i,k} A_i Y_{i,k} - \sum_{i=1}^{n} \sum_{k=1}^{t} A_i C_{i,k} \tag{3}$$

where U is the profit of the farm, expressed in millions of CLP (M CLP), where CLP corresponds to Chilean pesos; P_i is the price of the fruit crop i in the year k (M CLP t^{-1}); A_i is the area the fruit crop i is to be cultivated in (ha); Y_i is the yield generated by the crop i in year k (t ha^{-1}); and $C_{i,k}$ represents the production costs per unit area of the crop i in year k (M CLP ha^{-1}). Some of the components of $C_{i,k}$ are soil preparation, planting (the initial stage only), pruning, harvesting, fertilizers, and pesticides. The costs vary depending on how many years k it has been since the crop was planted.

Irrigation costs (IC) are associated with drip or microjet irrigation systems and correspond to the equipment's amortization per hectare. The costs related to soil preparation, planting, irrigation, and general orchard management during the first three years of the orchard's establishment, in which fruit crops do not produce significant yields, were also considered. To estimate these costs, a 17-year amortization period was considered. The capital recovery factor (CRF) [36] was calculated to equitably distribute the initial costs throughout the amortization period, resulting in annual payments that the company needs to make.

$$CRF = \frac{(1+i)^t \cdot i}{(1+i)^t - 1} \tag{4}$$

where i is the annual real interest rate (%) and t is the number of years over which the capital is amortized. The extended function is as follows:

$$\max U = \sum_{i=1}^{n}\sum_{k=1}^{t} P_{i,k}A_i\left[\alpha_i \cdot \left(\frac{ET_a}{ET_c}\right)^2 + \beta_i \cdot \left(\frac{ET_a}{ET_c}\right) + \gamma_i\right]Ym_i - \sum_{i=1}^{n}\sum_{k=1}^{t} A_i NL_{i,k} LC_{i,k} \\ - \sum_{i=1}^{n}\sum_{k=1}^{t} A_i OC_{i,k} - 10\,Csw \sum_{i=1}^{n}\sum_{k=1}^{t} A_i \frac{ET_a}{EA_i} - \sum_{i=1}^{n}\sum_{k=1}^{t} A_i IC_{i,k} \tag{5}$$

where LC is the cost of the labor required for the fruit crop i in the year k (M CLP person-day^{-1}); $NL_{i,k}$ is the labor required per unit area (person-day ha^{-1} year^{-1}); $OC_{i,k}$ corresponds to costs such as fertilizers, pesticides, and others; and Sw_k is the amount of surface water required in the year k (m^3 year^{-1}), with its corresponding cost being Csw (M CLP m^{-3}).

2.2.2. Model Constraints

The model includes constraints that guarantee the operational viability and sustainability of the orchard:

- Land availability: This constraint ensures that the total cultivated area does not exceed the total area available in the farm and is expressed as

$$\sum_{i=1}^{n} A_i \leq A_T \tag{6}$$

where A_T is the total land area (ha).

- Water availability: This constraint ensures that the sum of the gross water requirements of the fruit crops i in the year k does not exceed the farm's total water availability (W_T).

$$Wr_{i,k} = 10\sum_{i=1}^{n} \frac{A_i ETa_{i,k}}{AE_i} \tag{7}$$

$$\sum_{k=1}^{t} [SW_k - Wr_{i,k}] \leq W_T, \quad \forall k \tag{8}$$

where $Wr_{i,k}$ is the gross water requirement for each fruit crop i in the year k (m^3) and AE_i is efficiency of the irrigation system for the fruit tree i ($0 < AE < 1$). This variable is multiplied by 10 to convert mm to m^3.

- Minimum water applied: This constraint ensures that each crop receives the minimum amount of water required for crop development and productivity. The criterion used to determine the minimum amount of water applied to each crop in the year k is that it should not be less than 55% of the potential evapotranspiration of that crop, adjusted for the cultivated area. This value was obtained by analyzing the production functions presented in Table 1. This threshold is essential for preventing significant water stress, which could compromise both the crop yield and the sustainability of the agricultural system. Mathematically, this constraint is expressed as

$$ETa_{i,k}\, A_i \geq 0.55\, \cdot ETc_{i,k}\, A_i, \quad \forall i,k \tag{9}$$

- Labor availability: Given that the labor force can change from one year to the next, this constraint is expressed as

$$\sum_{i=1}^{n} A_i\, NL_{i,k} \leq La_k, \quad \forall k \tag{10}$$

where La_k is the total annual availability of labor per year k (person-day year^{-1}).

- Price risk constraint: This constraint aims to mitigate the financial impact of the volatility of market prices on the farm. It guarantees that the sum of the cultivated areas, weighted by a risk factor associated with the price volatility of each crop, does not exceed the acceptable risk limit for the farm. Mathematically, it is expressed as

$$\sum_{i=1}^{n} A_i r_i \leq R_{\text{Total}} \tag{11}$$

where r_i is the risk factor associated with the fruit crop i (adimensional). r_i is calculated as the ratio between the standard deviation of the price of the fruit crop and the maximum standard deviation observed among all fruit crops (Equation (12)).

$$r_i = \frac{DesvStd(i)}{DesvStd_{\max}} \tag{12}$$

In our model, the 'risk level' represents the uncertainty associated with the market price of fruit crops. The total risk limit, R_{Total} (ha), is determined by the farm manager and is expressed as a percentage of the total area (δ):

$$R_{\text{total}} = \delta \cdot A_{\text{Total}}; \quad R_{\text{total}} \geq r_i \text{ min} \tag{13}$$

This limit is conceptualized in terms of 'equivalent hectares of risk', a metric that quantifies the risk in relation to the size of the farm, facilitating risk management based on market price volatility and the farmer's risk tolerance.

- Crop area considerations: Agricultural, market, and productive diversity management criteria need to be considered in order to restrict maximum and minimum crop areas based on possible market or agricultural limitations. These constraints are expressed as follows:

$$min\, S_i \leq A_i \leq max\, S_i, \quad \forall k \tag{14}$$

where $min\ Si$ and $max\ Si$ correspond to the minimum and maximum crop area assigned to a farm producing fruit crop i, respectively (both in ha).

- Complementary considerations: A constraint is required to force the crop water requirement to assume a value greater than or equal to zero when the cultivated area is also zero, and this is expressed as

$$K \cdot A_i - \sum_{k=1}^{t} ETa_{i,k} \geq 0, \quad \forall k \tag{15}$$

where K is a positive constant (K = 10.000 mm ha^{-1}). In addition, to prevent the application of more water than the crop requires, the following constraint is added:

$$ETa_{i,k} \leq ETc_{i,k}, \quad \forall i, k \tag{16}$$

- Finally, there is a non-negativity constraint, which is expressed as

$$A_i, ETa_{i,k} \geq 0 \tag{17}$$

To aid readers in their understanding of the structure and functioning of the proposed model, Figure 1 contains a schematic diagram illustrating the relationships between the different components, including the model's objective function, constraints, input parameters (such as prices, costs, production functions, and potential evapotranspiration), and decision variables (the land and water allocation for each fruit crop).

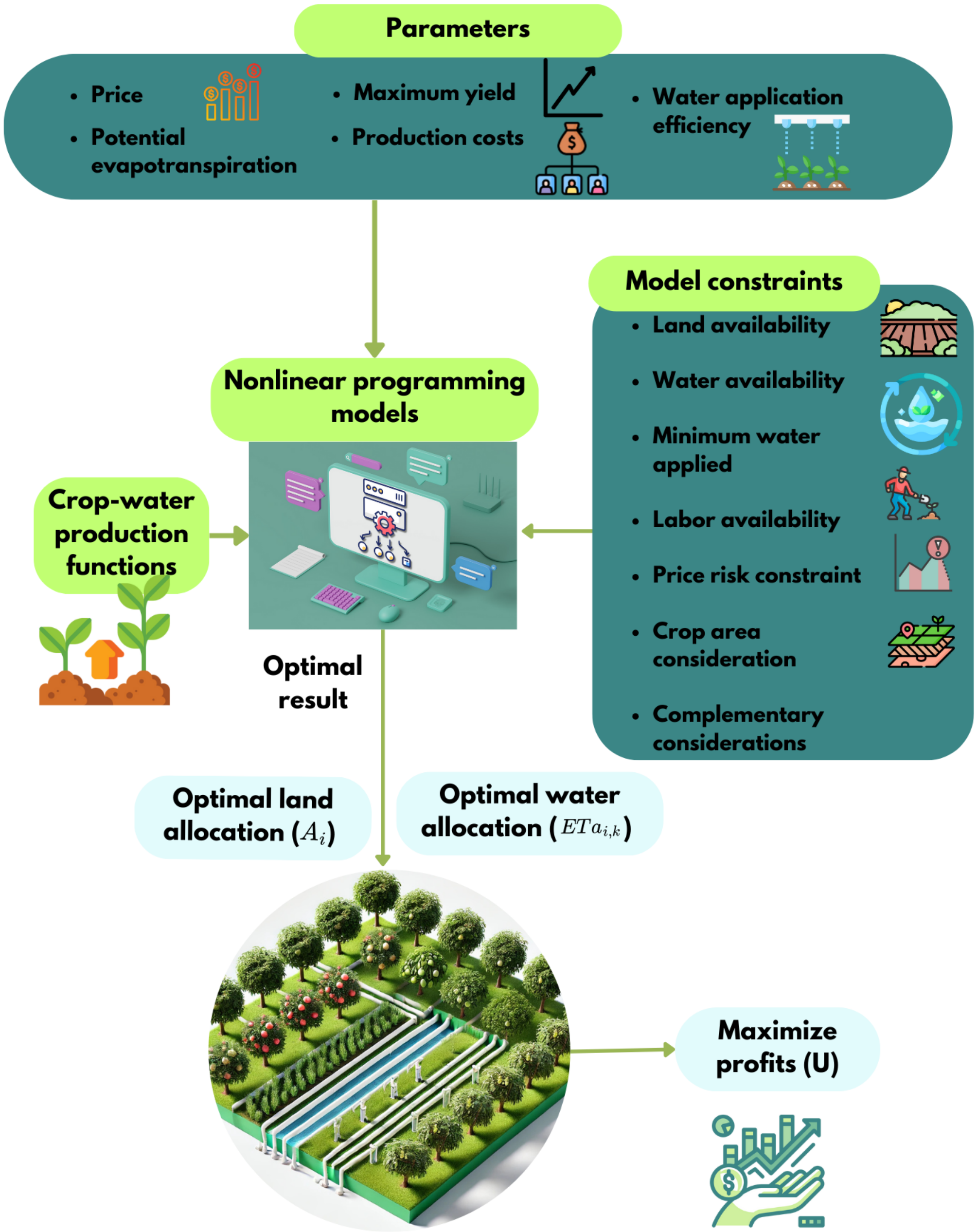

Figure 1. A schematic diagram of the nonlinear programming model developed for establishing the optimal cropping pattern for fruit orchards.

2.3. Study Site

The model was applied to the O'Higgins Region, which is located in the central valley of Chile (latitude 34°15′ S and 35°58′ S and longitude 70°30′ W and 72°00′ W) and covers an area of approximately 16,387 km² (Figure 2). The region's climate is predominantly Mediterranean, characterized by rainy winters and dry summers. The average annual precipitation in the region is approximately 652 mm, with concentrated rainfall mainly seen from May to August. The average annual temperature is 14 °C, reaching a maximum of up to 30 °C in summer and a minimum of up to 3 °C in winter [37].

The O'Higgins Region plays a key role in Chile's agricultural production, accounting for 26.9% of the total surface area of the country that is planted with fruit crops, including 24.2, 13.4, and 13.9% of cherries, table grapes, and citrus fruits (mandarins, oranges, and lemons), respectively. Other important crops are apples, pears, and avocados, for which they produce 4.6, 3.9, and 3.8% of the country's total, respectively. The region also contains 30% of the area covered by vineyards in Chile, making it the second most important region for wine after the Maule Region [38,39]. Since 2003, the area cultivated with cherries has increased by 799.3%, while table grapes have shown only a marginal increase of 0.5%. In addition, crops such as citrus fruits, apples, pears, and avocados have recorded changes of 20.0%, −35.3%, 14.0%, and 80.9%, respectively [38]. These variations in the cultivated area directly reflect the dynamics of the demand for and price of these crops in international markets, resulting in the expansion of the most profitable crops and a decrease in the planted area of the least profitable crops. Currently, the cultivation of crops such as kiwi and peach is rising, indicating farmers' continuous adaptation to market trends.

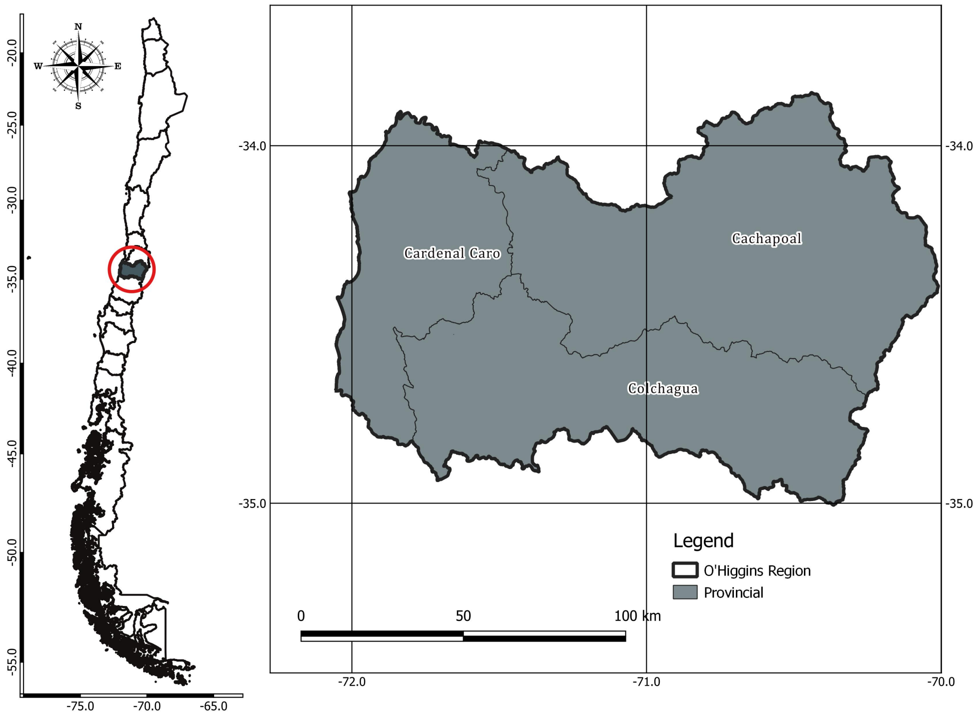

Figure 2. Map of the location of the study site.

2.4. Model Input Data

The fruit crops selected for this study are shown in Table 1, along with the empirical parameters of their production functions. Additionally, data on the maximum yields for each crop, compiled from various research studies, are presented in Table 2. These values represent the potential productive capacity of these crops under ideal agronomic conditions and optimized water management and serve as fundamental parameters in the crop water production function (Equation (2)). Yield estimates are adjusted based on applied water deficits or surpluses, allowing the model to simulate yield reductions in scenarios where the water applied deviates from the crop's optimal water requirements.

This analysis covers the 2000–2020 period, and export prices in US dollars (USD) for this period were obtained from the Office of Agrarian Studies and Policies (ODEPA) [40] (Figure 3). To convert these prices to Chilean pesos (CLP), the official exchange rate provided annually by the Central Bank of Chile was applied [41]. It should be noted that the exchange rate has experienced variations over time; however, in 2020, USD 1 was equivalent to CLP 792. Production costs were extracted from ODEPA's technical–economic reports [42] and were adjusted annually using the Consumer Price Index (CPI), which was provided by the National Institute of Statistics (INE). The annual water demand for each crop was calculated from local evapotranspiration references [43]. Potential evapotranspiration was then calculated using the crop potential factor (CPF) and based on the percentage cover model or leaf area index [44,45]. This measurement is crucial for estimating the exact water demand required by each crop under optimal conditions.

Table 1. Relative crop water production functions for the fruit crops analyzed using our model.

Fruit Crop	α	β	γ	Source
Blueberry	−0.6306	1.7716	−0.1204	Holzapfel et al. [46]
Cherry	−2.4364	3.1661	−0.0286	Carrasco-Benavides et al. [47]
Citrus fruit	−0.4664	1.0754	0.3962	Holzapfel et al. [48]
Peach	−1.3714	2.6952	−0.3238	Darshana et al. [49]
Kiwi	−0.7875	1.6847	0.1149	Holzapfel et al. [50]
Apple	−1.0448	2.0595	−0.0147	Darshana et al. [49]
Wine grape	−0.6604	1.1676	0.506	Jara et al. [51]
Table grape	−0.576	1.236	0.2827	Zúñiga-Espinoza et al. [52]
Pear	−2.3378	4.2551	9.966	Gomes et al. [53]
Avocado	−0.4462	1.1205	0.3257	Holzapfel et al. [54]

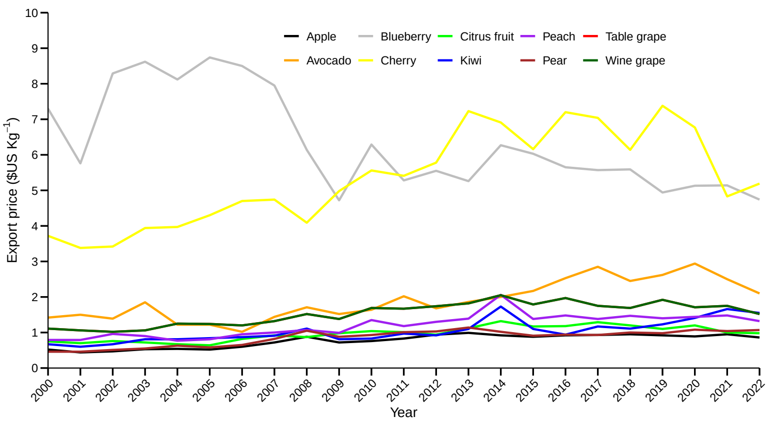

Figure 3. Trends in fruit export prices in the 2000–2022 period.

Table 2. Maximum yield of each fruit crop.

Fruit Crop	Maximum Yield (t ha^{-1})	Source
Blueberry	20	Holzapfel et al. [45]
Cherry	20	Blanco et al. [55]
Citrus fruit	70	Holzapfel et al. [48]
Peach	40	INIA [56]
Kiwi	45	Holzapfel et al. [50]
Apple	70	Lecaros-Arellano et al. [57]
Wine grape	25	Jara et al. [51]
Table grape	28	INIA [58]
Pear	50	ODEPA [38]
Avocado	25	Holzapfel et al. [54]

2.5. Model Evaluation

The optimization model was initially implemented without considering water and labor constraints, using General Algebraic Modeling System (GAMS) software, version 45, and solved using the SCIP solver. The GAMS is a robust and versatile tool used for solving optimization problems, renowned for its ability to handle complex nonlinear models and its flexibility in algebraic problem formulation [59]. Its architecture facilitates its integration with various solvers, allowing for the selection of optimal algorithms tailored to the specific nature and constraints of each scenario [60], thereby enhancing its efficiency and accuracy in the optimization process [61].

This initial configuration allowed for the identification of the maximum potential yield of the fruit crops, allowing for the addition of more objective constraints at later stages. The model was configured for a fixed area of 1000 ha, with irrigation and labor costs adjusted for inflation in order to reflect the projection of economic conditions over a 20-year period. For the year 2020, these costs were 10.17 CLP m^{-3} of water [26] and CLP 20,000 per working day [42]. Drip irrigation (AE = 0.9) was used for blueberries, cherries, oranges, peaches, kiwis, apples, wine grapes, table grapes, and pears, while microjet irrigation (AE = 0.85) was used for avocados.

An equitable surface distribution was carried out, allocating 100 ha to each type of fruit crop in order to assess their water and labor requirements, as well as their profitability. Subsequently, a detailed analysis was carried out on the risk associated with price volatility and the farmer's risk tolerance by applying the previously established risk constraint. Initially, the model did not limit the maximum area allocated to each fruit crop. However, an additional constraint was considered, limiting the maximum area per fruit crop to 350 ha to simulate how variations in risk level (100%, 80%, 60%, and 40%) influence the optimal cropping pattern. This approach is crucial to adapt the model to the farmer's preferences and mitigate possible economic losses, thus ensuring sustained profits amid market fluctuations.

Additionally, a detailed sensitivity analysis was conducted to assess how labor and water availability affect orchard management. A limit of 250 ha was established as the maximum area for each fruit crop. A progressive reduction in labor was simulated at intervals of 12.5%, 25%, 37.5%, 50%, and 67.5% to model different levels of labor shortage. Simultaneously, water availability levels were reduced by 12.5%, 25%, 37.5%, and 50% to represent different water restriction scenarios. This analysis allowed us to quantify the impact of the scarcity of these critical resources on land allocation and crop profitability, enabling us to adapt the agricultural strategies used in order to optimize crop management in the face of resource limitations.

To maximize profitability and ensure adequate crop diversification, several scenarios were analyzed, with both economic viability and resilience to variations in resource availability and market prices considered. The goal is for the results of the model to help inform decision making in critical situations such as water deficits, labor shortages, and price fluctuations. Although these variations may have affected profits, our findings can contribute to the adaptation of farming strategies, maintaining the viability and sustainability of orchards.

3. Results and Discussion

3.1. Homogeneous Fruit Crop Distribution Pattern

This section discusses the analysis of the profits from and water and labor requirements for each fruit crop over a 20-year period, considering a total surface area of 1000 ha equally distributed among the fruit crops. Figure 4A shows the different water requirements of each fruit crop throughout the study period. To conduct a detailed analysis of their water requirements, the 2019–2020 season was selected, as this was the period in which the highest water demand was recorded during the study. Figure 4B illustrates the specific water needs of each fruit crop evaluated during that season. This approach not only enables the identification of differences in water requirements among various fruit species but also provides a robust foundation for the optimal planning of fruit orchards based on water availability. In addition, Figure 5 presents the profits obtained and the labor required per crop.

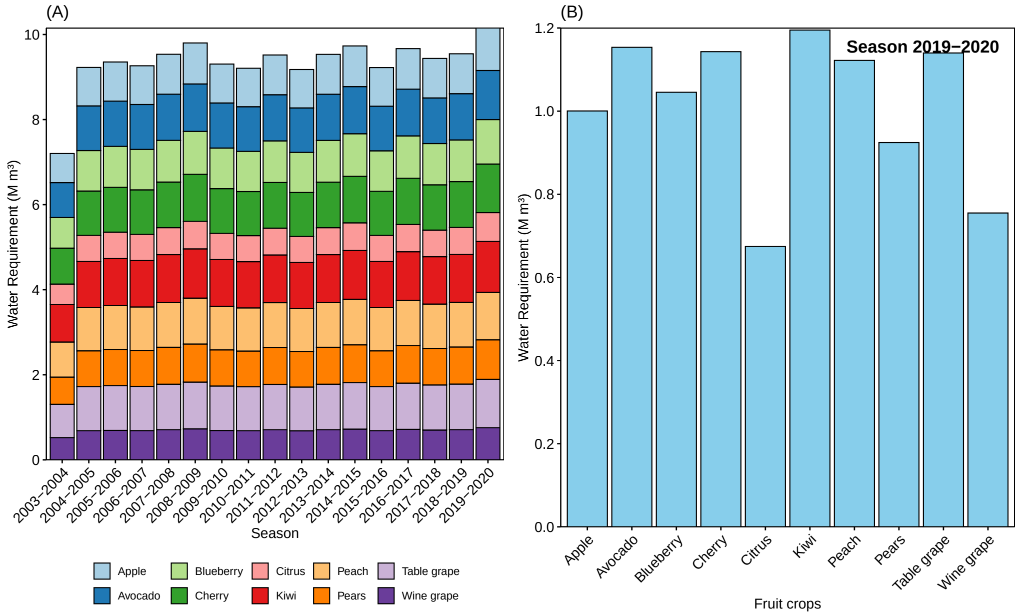

Figure 4. The water demand per season for each fruit crop when grown in homogeneous 100 ha areas (**A**) and their water requirements for the 2019–2020 growing season (**B**).

The analysis of how the water requirements changed over time revealed that the crops had a lower water demand during the 2003–2004 season, which was largely influenced by the plants' development under incomplete vegetation cover conditions. From the 2005–2006 season onwards, water consumption began to become more influenced by evapotranspiration, indicating that the crops had matured and there was an increase in water requirements. The highest water demand was recorded in the 2019–2020 season due to climatic conditions in the region (Figure 4B). Kiwis and avocados stand out for their high water requirements, which is in contrast to citrus fruits and wine grapes, which require significantly lower amounts of water. Understanding these differences is fundamental to implementing efficient water management, particularly in areas affected by water scarcity.

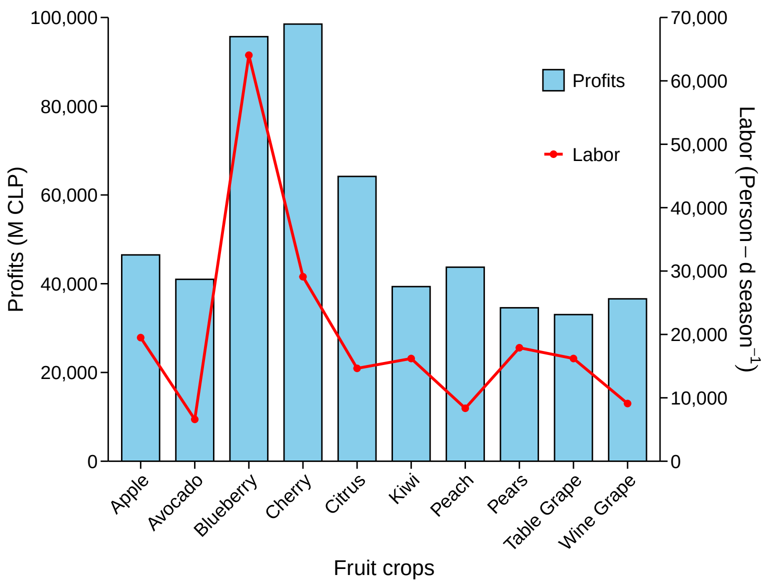

Figure 5. Profits generated and labor required for each fruit crop when grown in homogeneous 100 ha areas.

The analysis of the profits generated by fruit crops cultivated in equal areas of 100 ha (Figure 5) reveals significant differences between the crops over the study period. Cherries stand out as the most profitable fruit crop, followed by blueberries and citrus fruits. Peaches, apples, avocados, and kiwis show smaller profits, while the lowest profitability is observed in table grapes and pears. These data show the variability in the profitability associated with each type of fruit and highlight the importance of a strategic selection of crops to maximize economic benefits.

With respect to labor (Figure 5), blueberry stands out as the crop that required the highest number of labor days per 100 ha in the 2019–2020 season. Apples and pears are also labor-intensive, whereas peaches and avocados require significantly less labor. These findings underscore the importance of considering the availability of labor when allocating land for fruit orchards, particularly in places where labor is a limiting factor. Table 3 summarizes the average labor and water requirements for each fruit crop, as well as the profits generated when they are cultivated in equal areas of 100 ha.

Table 3. Profits generated and labor required for the analyzed fruit crops, considering an area of 100 ha.

Avg Labor Requirement (Person-d/Season)	Avg Water Requirement (m^3/Season)	Profit (M CLP)
192,943	9,480,158	533,143

3.2. Analysis of the Land Distribution Associated with Price Risk

Figure 6 shows the variation in the export prices of the fruit crops analyzed over the 2000–2020 period. The analysis of the standard deviation of their prices revealed that cherries and blueberries are the crops with the greatest fluctuations, although they generally correlate with higher economic returns. In contrast, apples, citrus, pears, and kiwis exhibit smaller fluctuations in prices, indicating their relative stability in the market. These results are crucial for adjusting diversification and risk management strategies in the allocation of land for fruit production.

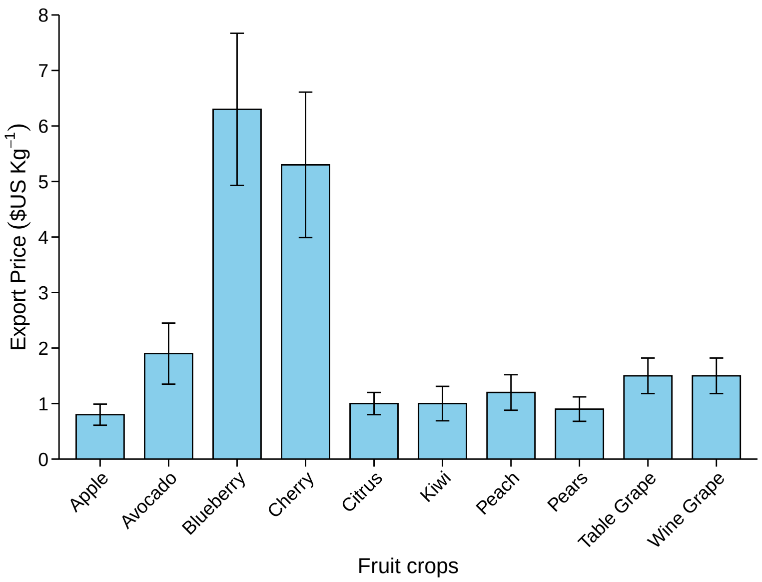

Figure 6. Export prices of the fruit crops studied.

Figure 7 presents the results of analyzing the area allocated to different fruit crops when no maximum area constraint is applied but their associated risk level is considered. This figure allows us to observe how the allocation of land varies in response to the different levels of risk assumed by the farmer. As the farmer opts to assume less risk, the size of the area allocated to cherry trees decreases, while the area dedicated to citrus trees increases. This phenomenon is mainly explained by the fact that although cherry trees offer high economic returns, they also exhibit the second highest price variability. In contrast, citrus trees, despite being third in terms of economic return, have lower price variability, which makes them a less risky option for the farmer.

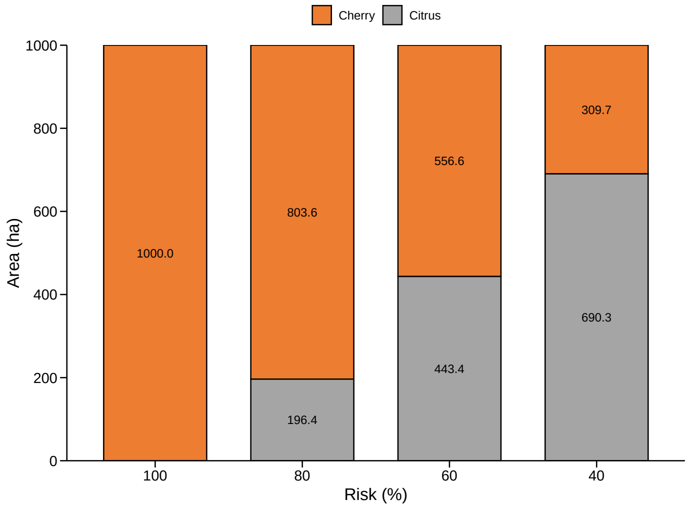

Figure 7. Land allocation in scenarios where different levels of risk are assumed by the farmer.

Table 4 shows the maximum labor and water requirements for this orchard, along with the profits generated under different risk levels. As the risk level is reduced, a decrease in water and labor demand is observed, as citrus fruits have lower water and labor requirements than cherries. However, these requirements are accompanied by a decrease in profits due to the lower economic return of citric fruits. Specifically, profits are reduced by 6.8%, 15.5%, and 24.1% when moving from a risk level of 100% to risk levels of 80%, 60%, and 40%, respectively.

Table 4. Labor and water requirements and profits generated at different risk levels.

Risk (%)	Avg Labor Requirement (Person-d/Season)	Avg Water Requirement (m^3/Season)	Profit (M CLP)
100	273,694	10,676,152	985,130
80	247,586	9,816,545	917,708
60	214,752	8,735,484	832,916
40	181,919	7,654,423	748,123

Establishing a maximum land allocation constraint of 35% of the total farm area has a marked effect on the risk level, as Figure 8 shows. This constraint provides a different perception of risk, as it forces diversification in order to mitigate the farmer's dependence on fruit crops with highly volatile prices. Specifically, assuming a risk level of 100% or 80% does not produce alterations in the cropping pattern. However, a risk level of 60% reduces the cultivation of blueberries and increases that of apples. Additionally, a risk level of 40% reduces the cultivated area of blueberries to an almost imperceptible value of only 4.8 ha, while the area planted with apples and peaches increases. This compensatory diversification is due to the low volatility of citrus fruit, apple, and peach prices, which balance the high risk derived from the high volatility of cherry and blueberry prices.

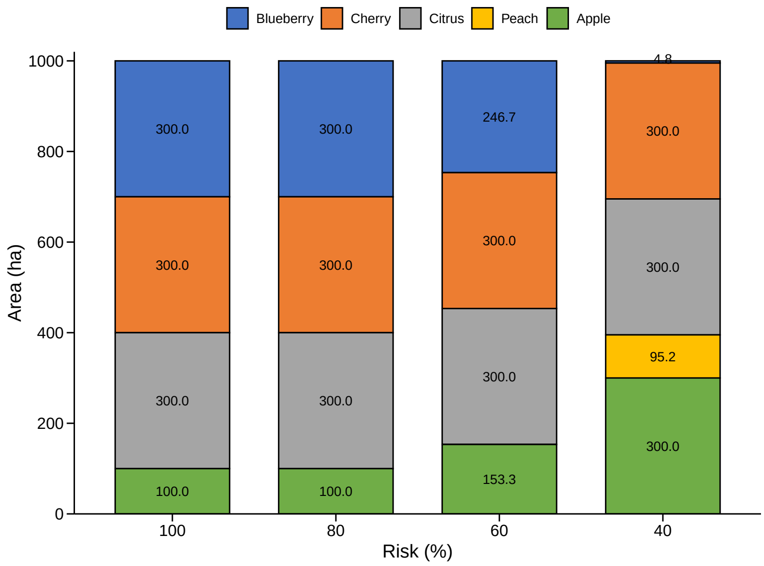

Figure 8. The land distribution of fruit crops when different risk levels are assumed by the farmer, with an area constraint of 35% of the total farm area for all fruit crops.

Table 5 shows the labor and water requirements of the orchard, as well as its corresponding profit outcomes, under the constraint of allocating a maximum of 35% of the total farm area to each crop and across varying risk levels, as defined in the 'Crop Area Considerations' (Equation (14)). As the risk level is reduced from 100% to 40%, there is a considerable tendency towards a decrease in labor requirements. This reflects a transition towards fruit crops with lower volatility and labor intensity, such as peaches and apples, which replace those with greater volatility and labor requirements, such as blueberries.

Despite changes in the cropping pattern, water consumption remains stable. This is attributed to the fact that the analyzed crops have similar water requirements, which facilitates efficient water management under the established constraints. In terms of profits, a consistent and significant reduction is observed. From the risk level 100% to 60%, profits decrease by 3.2%, while a more marked decrease of 18.0% is recorded from a risk level of 100% to 40%. These changes indicate that the selection of fruit crops with less volatile market prices has an important economic impact, resulting in lower returns but higher financial stability and predictability. This analysis confirms that although different risk levels modify the distribution of fruit crops, an adequate selection of crops can maintain an efficient water balance, which is essential for sustainable crop production in water scarcity scenarios.

Table 5. Labor and water requirements, and profits per crop, based on different risk levels, under the constraint that crops do not exceed 35% of the total farm area.

Risk (%)	Avg Labor Requirement (Person-d/Season)	Avg Water Requirement (m^3/Season)	Profit (M CLP)
100	325,149	8,955,335	821,609
80	325,149	8,955,335	821,609
60	302,660	8,932,573	795,403
40	200,773	8,937,287	673,780

When analyzing the allocation of land without a constraint on the maximum area for each fruit crop, there was a tendency to select one or two main fruit crops depending on the risk level. For example, cherries (high profitability and high volatility) and citrus fruits (good profitability and low volatility) dominated land allocation results, leading to significantly higher profits than those obtained under maximum area constraints. Specifically, the profits obtained at a 60% risk level without the constraint exceeded those at a 100% risk level with the constraint. However, the impact on profit was considerably lower under the constraint scenario, demonstrating that the effective diversification and distribution of fruit crops can reduce risk and protect against market volatility, promoting long-term financial stability and more efficient and sustainable risk management.

Furthermore, our analyses revealed that the water requirements seen at different risk levels and without a maximum area constraint vary widely due to the concentration of specific fruit crops. However, area constraints led to a notable stabilization in the demand for water, which resulted from broader diversification in the allocation of fruit crops adapted to different risk levels, thus preventing large fluctuations in water demand. This is crucial for the sustainability of agricultural operations, as it guarantees the efficient and predictable management of water resources, which is a determining factor in the long-term viability of agricultural practices under water scarcity scenarios.

3.3. Labor Sensitivity Analysis

The sensitivity analysis of labor availability reveals significant changes in land allocation and net profits, highlighting the importance of adequate crop planning. Figure 9 shows how the areas allocated to different fruit crops are adjusted as labor availability rates vary. The cultivation area of blueberries, which had an initial allocation of 250 ha, is reduced to zero as the labor available decreases to 37.5%, demonstrating the large amount of labor required by the crop. Regardless of their high labor requirements, cherries manage to maintain a constant allocation of 250 ha until the labor available drops to 50%, at which point their land allocation is reduced to 113 ha; this reduced but persistent allocation is explained by their high profitability. Citrus fruits maintain their full allocation of 250 ha at all labor availability rates, demonstrating that they have an optimal balance between labor requirements and profitability.

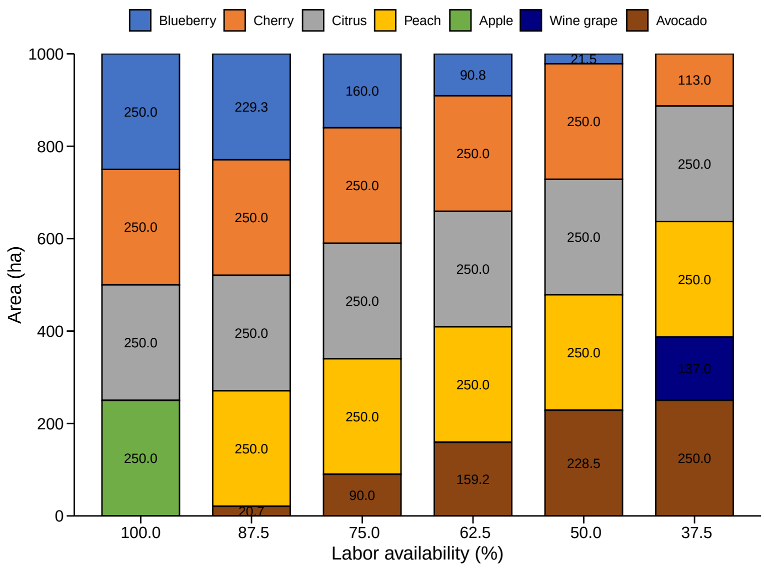

Figure 9. Land allocation of each crop under different labor availability rates.

The land allocated to apples is reduced to zero when the labor available reaches 87.5%, with peaches favored instead, as they have the second lowest labor requirements and offer only slightly lower returns. Simultaneously, the land allocated to avocados, which presents the lowest labor requirements, increases from 20.7 ha at 87.5% availability to 250 ha at 37.5%, highlighting their lower dependence on intensive labor. Wine grapes are third in terms of having a low labor requirement and are allocated 137 ha at the minimum labor availability. This allocation shows tactical adaptation, as crops with lower labor requirements and good returns are prioritized to optimize the use of available resources in response to labor constraints.

Table 6 shows how variations in labor availability directly affect labor, water use, and profits in fruit production. As the labor available decreases from 100 to 37.5%, a progressive reduction from 318,250 to 119,344 people per season is observed, resulting in changes in the land allocation of less labor-intensive fruit crops. Water consumption increases markedly when 87.5% of labor is available. At this point, the land allocated to apples, which require less water, is reduced to zero, while that allocated to peaches, which have higher water requirements, increases. As the labor available continues to decrease to 50%, a further increase in water consumption is observed, coinciding with an increase in the land allocated to avocados and a reduction in that allocated to blueberries. From the 87.5% level of labor availability, avocados, which require more water than blueberries, begin to occupy more area, increasing the water consumed. However, there is a decrease in water requirements when the labor available reaches 37.5%. This reduction is due to the decrease in the land allocated to cherries and the increase in that allocated to wine grapes, the fruit with the second lowest water requirements. The direct correlation between the decrease in labor availability and changes in land allocation reveals how changes in labor availability can cause significant variations in water requirements. This phenomenon not only directly affects the operation and sustainability of orchards under variable conditions, but also reflects that the strategic management of water resources should align with fluctuations in labor availability. This allocation pattern highlights the importance of the efficient integration of water resource management and labor planning to optimize the sustainability of agricultural operations, demonstrating that effective crop diversification and adequate planning can mitigate the impacts of labor and water availability issues.

In terms of net profits, our analysis shows that labor availability significantly influences profitability; the higher the amount of labor available, the less pronounced the reduction in profits. With full labor availability, profits are found to be CLP 762,162 M, and they decrease to CLP 533,676 M when the labor available is reduced to 37.5%, a 30% drop. This decrease illustrates the direct impact of labor constraints on the profitability of the fruit sector. Therefore, proactive land allocation planning that anticipates labor shortages can protect both the operation and profits of orchards.

Table 6. Maximum labor and water requirements and net profits under different levels of available labor.

Labor Availability (%)	Max Labor Requirement (Person-d/Season)	Avg Labor Requirement (Person-d/Season)	Avg Water Requirement (m^3/Season)	Profit (M CLP)	Reduction of Profits (%)
100.0	318,250	301,869	9,018,882	762,162	0.0
87.5	278,469	264,683	9,323,579	743,920	2.4
75.0	238,688	226,893	9,393,474	706,050	7.4
62.5	198,906	189,102	9,463,369	668,181	12.3
50.0	159,125	151,312	9,533,263	630,311	17.3
37.5	119,344	114,521	9,057,336	533,676	30.0

The integration of advanced technologies into agriculture, such as automated harvesting and other farm management practices, can significantly alter fruit cropping patterns. These innovations compensate for labor constraints and allow for the cultivation of labor-intensive but profitable fruit crops (e.g., blueberries and cherries) under labor shortage conditions. By reducing farmers' dependence on labor, these technologies not only improve operational efficiency but also strengthen the economic viability and sustainability of farms. This approach highlights the need to reevaluate farm optimization models to incorporate the impact of automation, ensuring that agricultural practices can adapt to future challenges.

3.4. Water Sensitivity Analysis

The water availability analysis reveals an interesting pattern in land allocation, highlighting the strategic variations made in response to the availability of water. As shown in Figure 10, blueberries, cherries, and citrus fruits maintain a constant allocation of 250 ha for all levels of water availability. This indicates that regardless of water restrictions, these crops are prioritized due to their profitability.

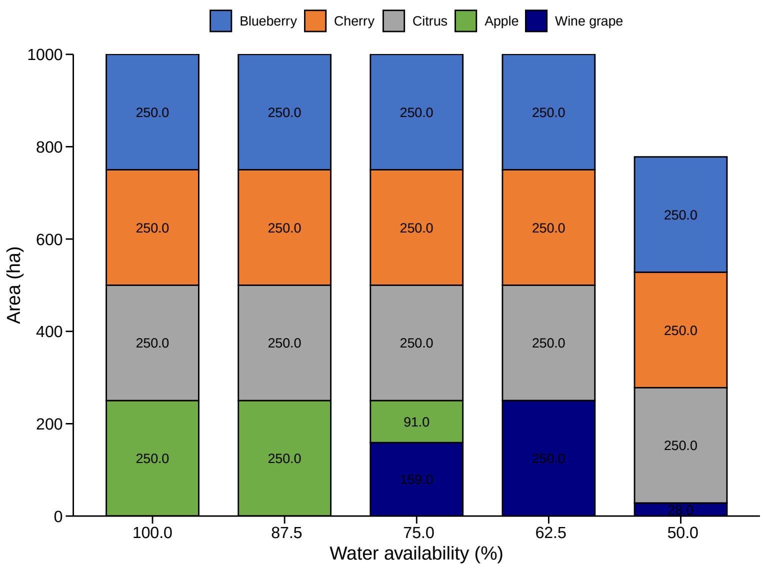

Figure 10. Land distribution under different levels of water availability.

The adjustment in the allocation of land between apples and grapes is particularly significant. With a reduction in water availability to 75%, the land allocated to apples decreases dramatically, from 250 to 91 ha, and eventually decreases to zero at 62.5% availability. Furthermore, the land allocated to wine grapes increases to 250 ha at 62.5% availability, before decreasing to 28 ha at 50%, indicating that their water requirements are lower than those of apples. This strategic adaptation is a response to the lower amount of water available, highlighting the importance of the efficient use of all available land area. While other fruit crops may offer higher returns than wine grapes, the crop that allows for a more complete use of the land under water restrictions is preferred, even if that crop is less profitable. With a water availability of 50%, only 778 of the 1000 ha is used. This demonstrates that the available water is insufficient to cultivate the entire farm.

The analysis of water use reveals interesting water management patterns in the face of water availability variations (Figure 11). At 87.5% availability, cherries are allocated more water than blueberries. Likewise, apples have higher water needs than citrus fruits. As the availability of water is reduced to 75%, the water allocated to blueberries increases compared to that of cherries, and an overall decrease in water volume is observed in citrus fruits. Simultaneously, the reduction in the water allocated to apples allows for the increased irrigation of wine grapes.

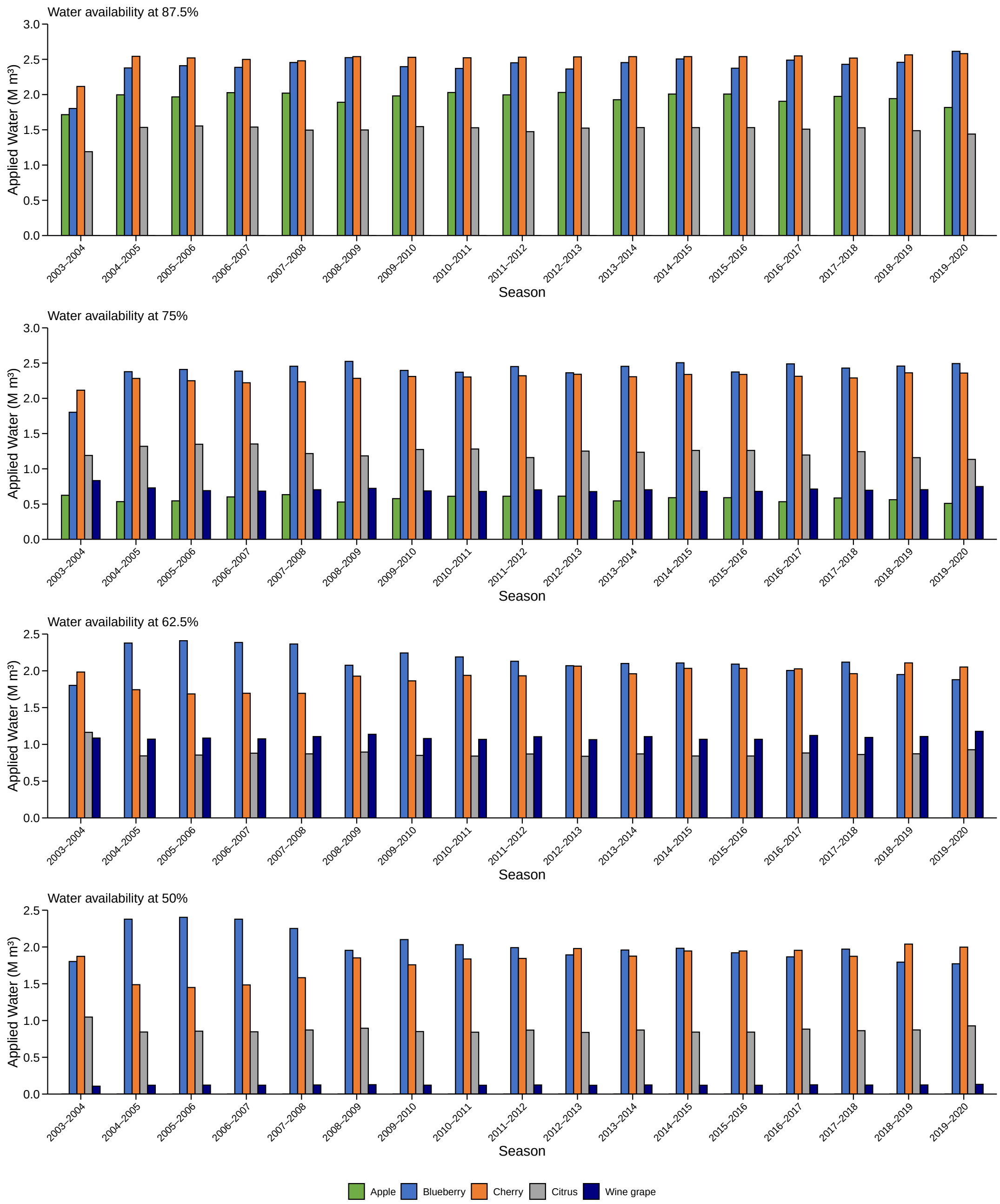

Figure 11. Water applied to fruit crops, given different levels of water availability, throughout the study period.

When reducing the availability of water to 62.5% and 50%, blueberries show an increase in their water allocation, particularly in the 2004–2005 and 2007–2008 seasons. This is explained by their high profitability and yield, which is directly related to the high market prices of blueberries recorded in those periods. As the water available decreases, a progressive reduction in the water allocated to cherries and citrus fruits is observed. In parallel, the water allocated to wine grapes initially increases when the water availability is 62.5% due to an increase in their cultivated area, but this then decreases as their area is reduced. This analysis underscores the importance of using adaptive water management to maximize the efficiency and profitability of the water used in the fruit sector under water deficit conditions.

After evaluating water management over several seasons and under different levels of water availability, our analysis focuses on the 2019–2020 season, the period with the highest recorded water demand, to thoroughly evaluate the allocation of water resources to fruit crops during peak demand. Figure 12 shows the amount of water applied per hectare for each fruit crop, considering the previously defined cropping pattern. It can be observed that even in the context of a progressive reduction in the water available, the high water requirements of certain crops such as blueberries and cherries are still met, highlighting their economic value and priority in water resource management.

The water allocated to citrus fruits is only reduced to 55% of their usual requirement at a water availability of 62.5%. Similarly, the water allocated to apples is reduced as the water available decreases until their land allocation decreases to zero. When the availability of water reaches 75%, land begins to be allocated to wine grapes and, despite variations in water availability, the amount of water they receive remains constant up to a water availability of 50%, reflecting the effort to optimize water use in less demanding crops when limited water is available.

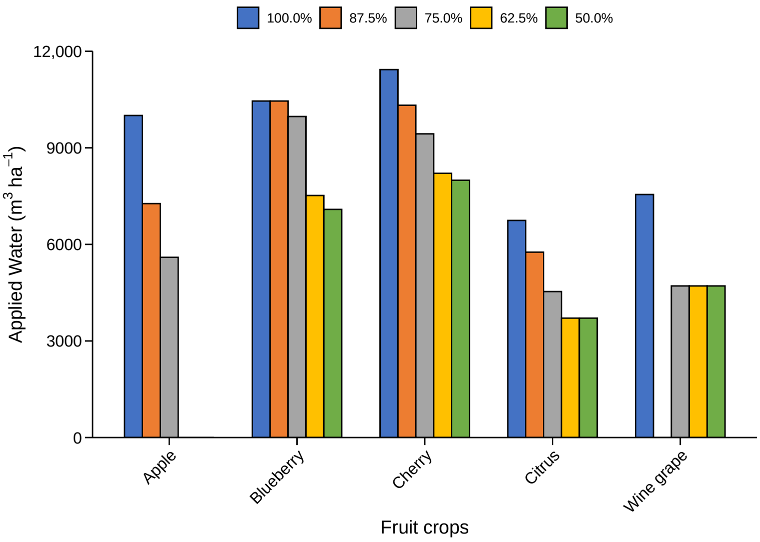

Figure 12. Water applied per hectare to select fruit crops in the 2019–2020 season.

Table 7 summarizes the combined effects of water availability and labor requirements on revenues in fruit production. As the water available decreases from 100 to 50%, we observe a proportional reduction in both labor and water requirements; labor decreases from 301,869 to 258,053 workers per season, while the maximum water requirement is significantly reduced from 9,658,391 m^3 to 4,829,196 m^3 per season. This is reflected in the profits, which fall from CLP 762,162 M to CLP 565,379 M, resulting in a reduction of 25.8%. It is important to note that the greatest diversification in the orchard was observed at 75% water availability, while the reduction in profits was relatively moderate, reaching 5.8%. This indicates that adequate management strategies can mitigate negative economic impacts even under significant reductions in water and labor availability. Finally, these results underscore the high sensitivity of fruit production to water, emphasizing the importance of the integrated and efficient management of labor and water resources. This adaptive capacity is essential in order for the sector to respond to fluctuations in resource availability and maintain profitability, ensuring that agricultural operations remain sustainable under uncertain conditions. The segmentation of land allocation is part of the strategic management of water resources, allowing farmers to prioritize crops with better adaptability to or higher economic returns under water stress scenarios. Their capacity to adjust the area allocated to crops according to the water available is crucial to maintaining economic viability under conditions of water uncertainty.

Table 7. Labor and water requirements and net profits when different levels of water are available.

Water Availability (%)	Avg Labor Requirement (Person-d/Season)	Max Water Requirement (m^3/Season)	Avg Water Requirement (m^3/season)	Profit (M CLP)	Reduction of Profits (%)
100.0	301,869	9,658,391	9,018,882	762,162	0.0
87.5	301,869	8,451,092	8,451,092	754,801	1.0
75.0	286,851	7,243,794	7,243,794	717,885	5.8
62.5	278,252	6,036,495	6,036,495	656,624	13.8
50.0	258,053	4,829,196	4,829,196	565,379	25.8

3.5. Optimum Cropping Pattern

In this section, we present the results obtained from the analysis of land and water allocation patterns that maximize water and labor use efficiency under potential scarcity conditions. Figure 13 illustrates the optimal amount of land to allocate to each crop, with the aim of maximizing profits and effectively managing the risk associated with price volatility and water and labor availability. This optimal pattern was determined after an exhaustive evaluation of different availability conditions, and it was selected because of its higher profitability and operational resilience. This strategy is designed to fit within the limits of the resources available. Table 8 presents both the average labor and water requirements for a cropping pattern with a 52% risk; this risk is due to the variability of fruit crops and the maximum availability of these resources. This comparison reveals that the operational requirements of this cropping pattern are substantially lower than the actual availability of these resources, which shows that the proposed pattern is highly efficient and sustainable.

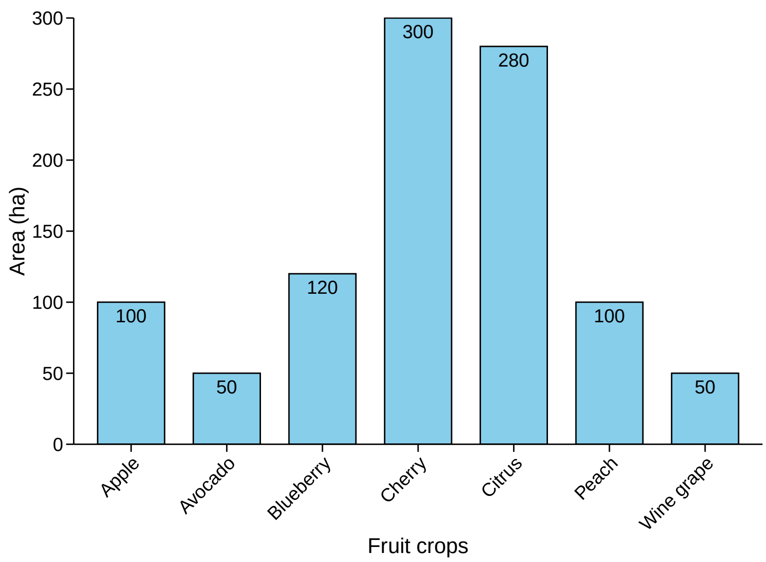

Figure 13. Optimum allocation of land to establish a cropping pattern in a fruit orchard.

Table 8. The availability and requirements of different resources, the risk level, and the profits generated by the optimal cropping pattern.

Max Labor Availability (Person-d/Season)	Max Water Availability (m^3/Season)	Max Labor Requirement (Person-d/season)	Max Water Requirement (m^3/Season)	Risk (%)	Profit (M CLP)
301,869	9,658,391	240,880	9,648,769	52	719,070

A sensitivity analysis focusing on water availability was performed to determine the resilience of the optimum land allocation pattern to water variations. The established pattern can operate effectively when the availability of water is reduced to 70%, highlighting its remarkable capacity to adapt to water deficits of up to 30%. Additionally, a comprehensive evaluation of the amount of water applied per hectare for each fruit crop was carried out according to the optimum cropping pattern. Figure 14 shows how water is distributed per hectare during the 2019–2020 season, considering various levels of water availability, which allows us to observe the adaptability of the system to different water availability conditions.

As the water available decreases, a general reduction in water consumption is evident for all fruit crops, which move from optimal supply levels to a threshold of 70%. This pattern is essential to preserving the economic viability of the orchard; the water supply to high-yield fruit crops such as blueberries and cherries is prioritized, while the water consumption of less profitable crops or those more tolerant to water deficits, such as wine grapes, is reduced. Specifically, the reduction in the water supplied to cherry, citrus fruit, peach, and apple occurs gradually as the water available decreases, while the reduction is more pronounced in avocado, which becomes stable when the availability of water falls below 77.5%. This analysis highlights the urgent need to establish cropping patterns that efficiently adapt to the variability of water availability, ensuring the long-term sustainability of agricultural operations in areas susceptible to water deficits.

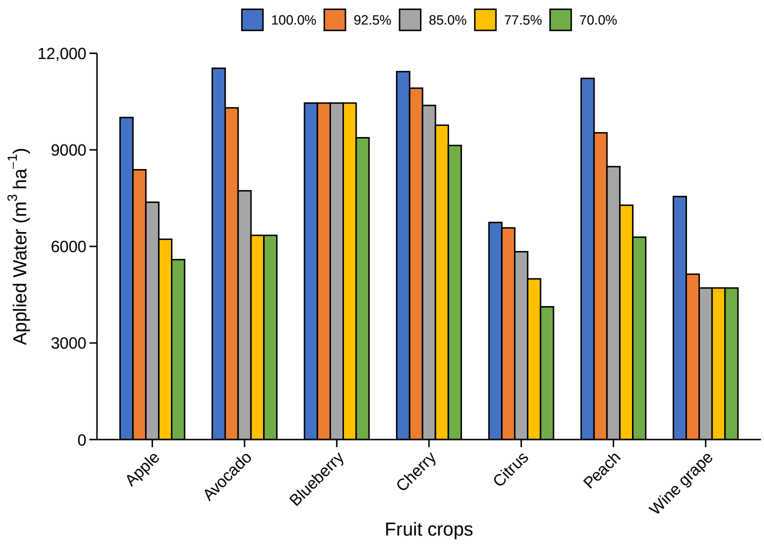

Figure 14. Water applied per hectare to selected fruit crops in the 2019-2020 season.

Table 9 shows how variations in the availability of water impact orchard profits, while also presenting the maximum labor and water required under different water availability conditions. When using the optimal pattern, the decrease in water availability does not affect labor requirements, which is attributed to the fact that this pattern employs 24% less labor than the maximum available. This strategy is adopted to minimize the orchard's dependence on labor, which is increasingly scarce, and to increase its long-term sustainability. In terms of profits, with a water availability of 85%, the reduction in the orchard's profits is only 1.4%. However, when this availability decreases to 70%, a more pronounced reduction in profits is observed, as these fall from CLP 719,070 M with full availability to CLP 661,443 M, representing a 7.8% decrease in profits. This analysis highlights the importance of efficiently managing water and labor resources when there are large changes in their availability.

Table 9. Labor and water requirements and net profits for the optimal pattern when different levels of water are available.

Water Availability (%)	Avg Labor Requirement (Person-d/Season)	Avg Water Requirement (m^3/Season)	Profit (M CLP)	Reduction in Profits (%)
100.0	228,810	9,009,919	$719,070	0.0
92.5	228,810	8,872,055	$717,917	0.2
85.0	228,810	8,209,633	$708,961	1.4
77.5	228,810	7,485,253	$690,910	3.9
70.0	228,810	6,760,874	$662,853	7.8

These analyses demonstrate that the optimal cropping pattern can respond effectively to variations in water and labor availability, maintaining its economic viability in different scenarios. Despite significant variations in the resources available, the stability in its profits highlights the strength and effectiveness of the proposed model. These results validate the implementation of agricultural strategies that respond to current conditions and proactively prepare for future challenges, ensuring the efficient and resilient management of fruit crops.

4. Conclusions

The proposed model determines optimal fruit cropping patterns in orchards over a 20-year period and includes a risk dimension to evaluate price volatility. This allows farmers to manage and select the most appropriate risk level for their orchards, with the annual allocation of water adapted to the specific conditions of irrigated agriculture in Chile between 2000 and 2020. The objective function of the model is based on production functions, which were used to estimate fruit yields. The model includes critical variables such as the maximum evapotranspiration recorded in the region, labor requirements, production costs, and annual sale prices.

However, this model is limited due to its theoretical nature, which prevents it from capturing the full complexity of agricultural reality. Even though resource allocation is optimized, the model does not consider factors such as pests and soil fluctuations, which can affect actual yields. Furthermore, the equations apply to annual periods and ignore short-term variations and changes occurring in the cropping area during the study period. These limitations indicate that this model is a complementary tool rather than an accurate representation of agricultural reality.

The initial analysis conducted, with 100 ha allocated to each crop, revealed significant differences in the crops' water and labor requirements, as well as their profitability, highlighting the importance of strategically selecting crops to maximize profits. The results showed that without maximum area constraints, allocating the entire area to one crop such as cherry can be highly profitable but also risky, due to the orchard's dependence on a single market and the volatility of fruit prices. The risk assessment revealed that by reducing risk, the land allocated to stable crops such as citrus fruit and apple increases, while that allocated to volatile crops such as cherry and blueberry decreases. Therefore, farming practices need to be adapted to respond to different market uncertainty scenarios. Furthermore, sensitivity analyses of labor and water availability showed that potential variations in these areas have substantial impacts on the planning and sustainability of orchards. The adaptability of cropping patterns to these variations is vital to maintaining the economic viability of an orchard. The optimal cropping pattern showed an ability to adapt to reductions in water availability of up to 70% and reductions in labor availability of 24%, ensuring economic sustainability under various scenarios. The stability of its profits, despite these variations in resources, underlines the effectiveness of this cropping pattern and the proposed allocation of water for sustainable management.

In conclusion, the implementation of agricultural strategies that efficiently integrate water use and labor management is crucial for the economic and environmental sustainability of fruit production. The findings of this study indicate that proactive approaches, including crop diversification and balanced resource allocation, need to be implemented to prepare for future challenges and mitigate the risks associated with price volatility and the fluctuating availability of essential resources. Future research should consider integrating the developed model into decision support systems (DSSs) to assist farmers and agricultural managers in the optimal planning of crops and resource allocation. These systems can provide tailored recommendations based on the specific conditions of each farm, helping to maximize profits and efficiently manage water and land resources. Furthermore, researchers should explore optimal cropping patterns at the basin scale, integrating annual and perennial crops into this assessment and extending the study period, thus allowing for the more strategic and sustainable management of agricultural resources. In water deficit scenarios, the prioritization of the water allocated to fruit crops is recommended, given their perennial nature and the long-term investment they represent, and also as annual crops have shorter and more flexible life cycles. The land allocated to annual crops serves as a buffer area, providing additional flexibility and resilience in resource management.

Finally, it is important to note that the incorporation of advanced technologies such as irrigation and harvest automation could redefine these patterns by optimizing operational efficiency and mitigating labor shortages. This would allow for the more strategic and sustainable management of water resources, ensuring the economic and environmental viability of agricultural practices in regions susceptible to water supply constraints. This approach addresses current needs while also preparing for future challenges in agricultural management.

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