agriculture

Review

The Ecosystem Services of Irrigated Orchards: A Review

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Abstract

In the context of global population growth and intensifying climate change, ensuring food security remains a critical challenge. Orchards are more productive than arable crops, contributing significantly to the nutrition of a growing population. Ecologically, due to the absence of frequent soil tillage, orchards resemble natural forest ecosystems more closely than other agricultural systems. Irrigated orchards are particularly productive and enhance biodiversity in territories where water scarcity is the limiting factor for ecosystems. This review, the result of extensive reflection and a comprehensive analysis of the literature on orchard sustainability, synthesizes evidence on the diverse ecosystem services provided by these perennial systems. Due to their structural complexity, well-managed orchards contribute significantly to climate regulation through carbon sequestration, microclimate cooling, and soil erosion prevention. Furthermore, they support nutrient cycling and provide cultural value. This paper establishes an integrated scientific framework to inform evidence-based policies and reshape societal perceptions. It argues that recognizing orchards as multifunctional landscapes, rather than mere resource consumers, is critical for environmental resilience, supporting their fair valuation as essential components of a sustainable bioeconomy.

Keywords: agroecosystem; biodiversity; carbon sequestration; climate change; evapotranspiration; food security; irrigation; pollination; soil microbial communities; sustainability

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1. Introduction

While the ecosystem services of forests are well-documented [1–3], human-managed agroecosystems remain comparatively understudied, despite their global relevance and varying degrees of anthropization. Orchards represent a notable example. Although often perceived as highly polluted agroecosystems due to the traditionally intensive use of pesticides [1], they are perennial, woody and vertically stratified ecosystems that exhibit substantial structural complexity and ecological functionality, particularly when incorporating cultural practices that enhance biodiversity and soil health [4,5].

Irrigated orchards represent a unique category. They often resemble productive forests in canopy structure, biomass accumulation, and carbon sequestration potential [6], while being primarily oriented toward fruit production rather than ecosystem services [7,8]. Their perennial nature, combined with continuous water availability, can support a wide range of ecosystem services, including microclimate regulation, soil stabilization, pollination support, and habitat provision for beneficial organisms. However, high input intensity, advanced management technologies, and strong market orientation distinguish irrigated orchards from natural or semi-natural forests and may influence the type and magnitude of ecosystem services they provide [9].

Although orchard ecosystem services have been documented [10], they remain underrepresented in scientific literature, particularly in the context of irrigated orchards. Existing research typically focuses on individual services such as pollination, pest regulation, or carbon storage [11], rather than adopting a holistic, multifunctional perspective. Despite their increasing importance, there is still a lack of integrative studies that comprehensively assess irrigated orchards as complex socio-ecological systems. This limitation is particularly relevant, given the rapid expansion of these systems in Mediterranean and semi-arid regions, where they are central to rural economies, land-use change, and water dynamics. In this context, a systematic synthesis of existing knowledge is imperative.

This paper aims to address the existing gap in the literature by providing a comprehensive and integrative perspective on irrigated orchards as multifunctional agroecosystems. Specifically, the objectives of this review are:

(i) to synthesize existing knowledge on the ecosystem services associated with irrigated orchards;
(ii) to provide an integrated and critical perspective on the conceptualization of these systems in the scientific literature, particularly in relation to their ecological and socioeconomic roles;
(iii) to identify key knowledge gaps and highlight future research needs, particularly regarding the relationships between management practices and ecosystem service provision.

Accordingly, this study addresses the following research questions:

(i) What types of ecosystem services are associated with irrigated orchards?
(ii) How are irrigated orchards conceptualized in the literature, and to what extent are they recognized as providers of ecosystem services?
(iii) What are the key knowledge gaps and research needs regarding the relationship between irrigated orchard management and ecosystem service provision?

2. Methodology

This review focuses on the role of irrigated orchards in the provision of ecosystem services. Therefore, other permanent crops, including herbaceous plants (e.g., banana), climbers (e.g., grapevine, kiwi), shrubs (e.g., berries, tea), cacti (e.g., pitaya, prickly pear), palms (e.g., coconut, oil palm, date palm), and species cultivated for non-fruit products (e.g., cinnamon, rubber), are not considered orchards and are excluded from this review.

This review is based on an extensive literature survey comprising more than 300 articles. Searches were conducted through the b-On (Online Knowledge Library), which provides access to major scientific databases (e.g., Web of Science and Scopus) using keywords such as “orchard” OR “olive grove,” combined with service-specific terms, such as “transpiration”, “microclimate”, “water infiltration”, and “water retention” for microclimate regulation and water regulation services, and “carbon sequestration”, “carbon storage”, and “soil organic carbon” for carbon sequestration and storage. To quantify the role of orchards in food production and to estimate their caloric and nutritional productivity, open access databases from FAOSTAT (https://www.fao.org/faostat/en/#data/; accessed on 6 October 2025) and USDA FoodData Central (https://fdc.nal.usda.gov/download-datasets; accessed on 6 October 2025) were used. Maps illustrating wildfires between 2020 and 2024 and irrigated orchards in the Algarve region (Portugal) were produced using QGIS 3.40, based on open access data from the *Instituto da Conservação da Natureza e das Florestas* (ICNF) and the *Instituto de Financiamento da Agricultura e Pescas* (IFAP).

The literature was analyzed using an integrative and qualitative approach, aiming to provide a comprehensive synthesis of current knowledge on irrigated orchard ecosystem services.

3. The Orchard as an (Agro)Ecosystem

An ecosystem is "*a system in which living things (plants, animals, bacteria,* etc.*) and their non-living surroundings interact as a functional unit*", according to the European Union [12]. Similarly, the Convention on Biological Diversity describes it as "*a dynamic complex of plant, animal and microorganism communities and their non-living environment interacting as a functional unit*" [13], a definition widely adopted also by the European Environment Agency, among other entities [14].

When referring to human-modified ecosystems dedicated to agricultural activity, a more specific term is used: **agroecosystem**. The Biodiversity Information System for Europe (BISE), based on established literature [15], defines agroecosystems as "*communities of plants and animals interacting with their physical and chemical environments that have been modified by people to produce food, fibre, fuel, and other products for human consumption and processing*" [16]. Thus, an **orchard** is a specialized agroecosystem designed for the cultivation of fruit or nut-producing trees (perennial woody species), typically arranged in a systematic and managed layout to optimize productivity [17].

Within orchard agroecosystems, management intensity varies along a gradient from extensive to super-intensive systems, reflecting distinct production objectives. A system becomes more intensive as greater amounts of external inputs are added. Extensive orchards are characterized by low planting densities [18,19] and rely primarily on natural ecosystem processes, with minimal investment per unit area (Figure 1a). These systems generally depend on natural resources, such as rainfall and inherent soil fertility, involving few external inputs and resulting in low productivity and limited economic return per hectare [20]. Conversely, intensive (Figure 1b) or even super-intensive (Figure 1c) orchards aim to maximize yields by fully exploiting the cultivated area. This is achieved through higher planting densities [19,21] and the application of external inputs (water, fertilizers, and phytopharmaceuticals) to optimize growth conditions.

Intensification may affect orchard ecosystem services in contrasting ways. Highly intensive systems generally show greater productivity and short-term carbon sequestration than water-stressed or pest-affected systems [22]. However, intensive mineral nitrogen fertilization also increases nitrate leaching and N_2O emissions [23]. In orchards receiving 140 kg N ha^{-1} yr^{-1} of mineral fertilizer, nitrate leaching reached 45–55 kg NO_3 ha^{-1} $yr^{-1,}$ whereas organic or unfertilized systems remained below 10 kg NO_3 ha^{-1} yr^{-1} [24]. Nevertheless, irrigation and fertilization can enhance carbon sequestration in biomass and soil, thereby achieving a more favorable balance between carbon sequestration and greenhouse gas emissions [22,23].

Ecosystem service provision therefore depends on (i) biological factors; (ii) edaphoclimatic conditions [25]; and (iii) management practices, which explained up to 78.5% of the observed variance in simulated ecosystem services in other studies [24].

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In irrigated orchards, irrigation acts as an intensification factor at multiple levels. First, it is an intensifier in itself, increasing the total volume of inputs applied while also enabling fertigation. Second, irrigation allows higher planting densities, thereby increasing demand for external inputs.

(a) (b) (c)

Figure 1. Different levels of intensification in almond (*Prunus dulcis*) orchards: (**a**) extensive rainfed orchard with irregular spacing (Algarve, Portugal); (**b**) intensive irrigated orchard (6 m × 4 m) (Alentejo, Portugal); (**c**) super-intensive irrigated orchard (3.5 m × 1.2 m) (Alentejo, Portugal).

4. Ecosystem Services and Externalities

Ecosystems provide a wide range of benefits known as **ecosystem services** [26]. In orchard agroecosystems, some authors propose the term "**agroecosystem services**" to emphasize the human-managed nature of these benefits [27–29]. Following the Millennium Ecosystem Assessment framework, these services are categorized into four groups: provisioning (material goods like food), regulating (climate or water regulation), cultural (recreational or spiritual benefits), and supporting (nutrient cycling and soil formation) [26].

From an economic perspective, these services relate to **externalities—**positive or negative effects of economic activities on third parties that are not reflected in market prices [30]. While fruit production is a provisioning service, its nature as a private, tradable good often centralizes it in a "productivist" view, overshadowing the orchard's role as a provider of public goods. However, an environmental perspective recognizes that orchards generate both positive externalities (derived from ecosystem services like carbon sequestration) and negative externalities (arising from ecosystem disservices, such as nutrient leaching). As summarized in Table 1, many negative externalities can be mitigated through appropriate territorial planning and sustainable management.

Table 1. Examples of potential positive and negative externalities provided by orchards, including environmental, socioeconomic, and cultural dimensions, depending on management practices and other influencing factors.

	Positive Externalities	Negative Externalities
Environmental	• Carbon sequestration [31] • Soil stabilization and erosion control [32–34]. • Enhancement of biodiversity [35,36]. • Microclimate regulation [37,38]. • Wildfire spread control [39,40].	• Agrochemical runoff and groundwater contamination [41]. • Greenhouse gas emissions (e.g., machinery, fertilizers, residue burning) [42,43]. • Depletion of water resources [44] • Soil and air pollution [45,46] • Loss of natural habitats [47]. • Soil degradation [48,49]. • Biodiversity decline and pollinator loss [50,51].

Table 1. *Cont.*

	Positive Externalities	Negative Externalities
Socioeconomic	• Employment: Direct (permanent and temporary); and indirect (related sectors) [52]. • Food security: Availability, access, utilization, and stability of food for the population [53]. • Rural development: Retaining population in rural areas [54]. • Local economic resilience [53].	• Occupational hazards and job precariousness [55] • Competition for land and water resources
Cultural	• Preservation of traditional agricultural knowledge [17]. • Preservation of cultural landscapes • Reinforcement of regional identity [17,56–58]. • Enhancement of agritourism potential [59,60]. • Community cohesion	• Homogenization of the landscape [61] • Loss of cultural diversity [62] • Degradation of scenic beauty [61,62]

5. Provisioning Services

5.1. Food Production

This ecosystem service directly contributes to food security, a critical contribution to society in the current global context, from both humanitarian and geopolitical perspectives. According to the United Nations, food security is based on four pillars: (i) availability, the physical existence of food; (ii) access, the ability of individuals to obtain it; (iii) utilization, the appropriate use of food regarding nutritional value, quality, and safety; and (iv) stability, the consistent performance of the three preceding pillars over time [63].

Food production is the main purpose of orchards, providing tradable products that generate income and justify investment in the establishment and maintenance of orchards. Despite occupying only slightly more than 4% of the utilized agricultural area, orchard systems account for approximately 5% of total crop production (Figure 2), reflecting their high productivity per unit area. In contrast, annual crops, particularly cereals, legumes, and oilseeds, dominate land use, covering nearly 80% of cropland, yet contribute only around 43% of total production due to their lower productivity. This contrast underscores the disproportionate contribution of orchards to the food provisioning ecosystem service, highlighting their strategic role in efficient land use and in strengthening food security within multifunctional agricultural landscapes.

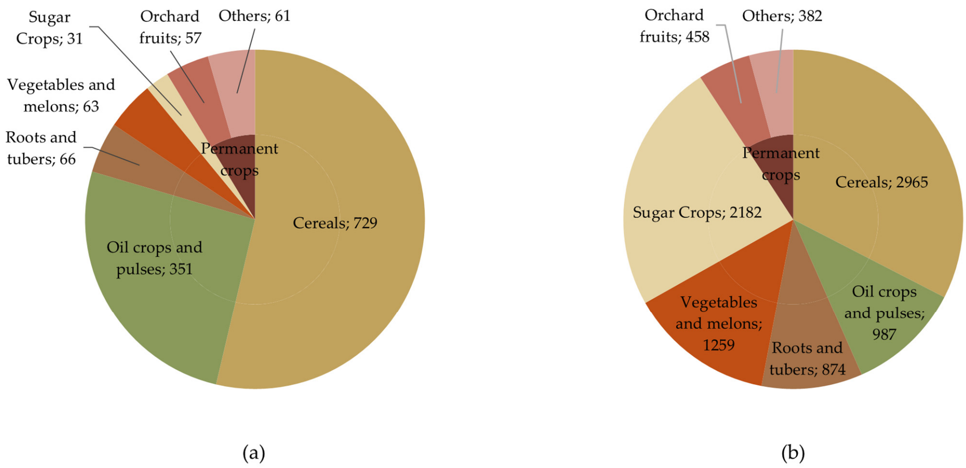
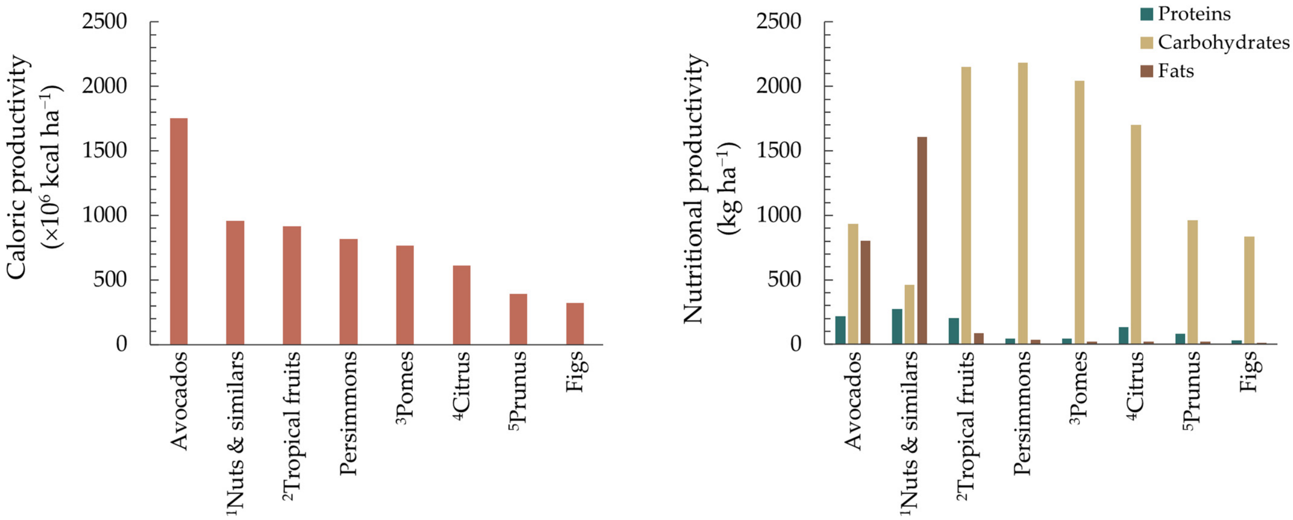


Figure 2. Global production of non-animal food: (**a**) Cultivated area (values in $\times 10^6$ ha; 10-year average, 2013–2024); (**b**) Production (values in $\times 10^6$ t; 10-year average, 2013–2024). Notes: Sugar crops include all sugar crops, including non-food uses. Source: FAO, 2023 [64].

Within orchards, crops can be grouped by fruit type, with each group contributing differently to meeting human energy requirements. Avocado is the most productive crop in terms of calories per unit area, producing nearly twice as much as the next most productive group, nuts and similar (Figure 3a). Although nuts and similar crops contain more than three times the calories per unit of product weight, their productivity per unit of cultivated area is considerably lower than that of avocado. Fruits and nuts contribute to global energy intake but play a complementary role compared to cereals, which remain the main calorie source worldwide [65,66].

However, under the third pillar of food security, foods must meet the population's nutritional requirements, extending beyond energy provision alone. From this perspective, nuts and similar crops produce the highest amounts of protein and fat per unit area (Figure 3b). When considering fresh fruits only, avocado stands out as the fruit with the highest protein and fat yields per unit area (Figure 3b). Most other crop groups are considerably more efficient in producing carbohydrates (natural sugars and dietary fiber), while their protein and fat yields remain marginal. That said, nutritional value is not determined solely by the three primary macronutrients. These fruits are also important sources of vitamins (e.g., vitamin C in citrus and vitamin A in apricots) [67,68], minerals (e.g., potassium in avocados) [69], and antioxidants (e.g., polyphenols in blood oranges and pomegranate) [70–74]. Fruit quality, including both internal attributes [75] and external appearance [76–78], is also essential for consumer acceptance and market value.



(a) (b)

Figure 3. Nutritional productivity of different fruit groups commonly consumed fresh and nuts cultivated in orchards worldwide: (**a**) caloric productivity; and (**b**) nutritional productivity. Notes: In groups comprising multiple crops, the group average was calculated. [1] Nuts and similar: cashew, almonds, walnuts, hazelnuts, pistachios, karité nuts, and chestnuts; [2] Tropical fruits: mangoes, guavas, papayas, and others. [3] Pomes: apples, pears, quinces, and others. [4] Citrus: oranges, mandarins, lemons and limes, grapefruits, and others. [5] Prunus: plums, apricots, peaches, cherries, nectarines, and others, excluding almonds. Sources: FAO, 2023 and USDA, 2020 [64,79].

5.2. By-Products Production

By-products are secondary outputs of a production process, lower in value than the main product, legally usable, and derived from the same process, but they may still hold economic value as complementary or collateral outcomes [80].

Vegetative by-products, such as pruning residues, can serve multiple purposes. Although typically shredded and left in the orchard inter-rows [81], larger materials, such as thick branches, can be collected and utilized for energy production [82]. These residues can be shredded and densified into pellets, which can subsequently be used as a solid fuel in boilers, furnaces, or heating systems [83,84]. Pellets from branches have higher calorific value and lower ash content, making them suitable as biofuels, while those including leaves are limited by high ash, nitrogen, sulfur, and heavy metal content [83]. Considering that their calorific value differs between species [85]. On the other hand, leaves and flowers, such as those from citrus trees, can be used to produce other by-products, including essential oil [86–90] or animal feed [91–93]. Pruning residues and other by-products, such as nut or almond shells, can also be used as livestock bedding [94,95]. Shells may additionally serve as mulch in orchards, reducing the need for weed control and contributing to soil carbon storage and nutrient cycling [6].

5.3. Complementary Productions

Orchards can support complementary livestock production, which, although not the primary objective, provides additional benefits including enhancing nutrient cycling, improving soil fertility, and contributing to vegetation and pest management [96–100]. However, the increasing demand for animal-source foods places significant pressure on forested areas due to the extensive land requirements of livestock production [101,102]. In this context, integrated crop–livestock systems offer a relevant alternative, as they are consistently associated with lower environmental impacts than conventional specialized systems [103], while also improving overall land-use efficiency.

The relationship between intensification and grazing varies significantly. While extensive orchards are characterized by low planting densities, which facilitate the use of inter-tree spaces for pasture [17], grazing is not exclusive to these systems. It also occurs in more intensive orchards [104], where the integration of livestock acts as an additional layer of intensification. Integrating livestock increases resource use per unit area, enhances overall productivity and provisioning services, and promotes greater on-farm biodiversity.

Not all livestock species are equally suitable for integration into orchards. Larger animals, such as cattle, have high space requirements [105]; however, their integration may become feasible in extensive orchards [106]. Highly opportunistic feeders, such as goats, may consume a wide range of plants, including woody parts, potentially affecting tree growth and orchard management [107]. Due to their selective grazing behavior, sheep are well-suited for weed control with minimal impact on fruit crops [108] (Figure 4a). Sheep generally do not require enclosed night shelters, but adequate shade is essential, especially during summer (Figure 4b). Irrigated orchards provide superior cooling compared to other agroecosystems, even at wider spacings (e.g., carob orchards), as water availability enhances transpiration and soil evaporation, improving microclimatic regulation [109].

Accordingly, livestock can be integrated into orchard systems at three different levels: (i) continuous and intensive integration (high level of integration); (ii) seasonal integration with agronomic adjustments (intermediate level of integration); or (iii) opportunistic or collaborative integration (low level of integration) [104]. At the highest integration level, animals remain in orchards year-round, improving weed control and reducing costs, but increasing herbaceous management complexity and sometimes requiring adjustments to tree training systems [98,104]. At the lowest integration level, grazing is occasional and often involves external livestock producers, promoting resource sharing and reducing labor for the fruit grower. However, it requires coordination and depends on supplementary grazing areas during key periods (spring and autumn) [104]. Some livestock by-products can be reintegrated; for example, low-value wool can be used as mulch [110,111] (Figure 4c).

(a) (b) (c)

Figure 4. Livestock integration in irrigated orchards: (**a**) a flock of sheep grazing in an avocado orchard (Algarve, Portugal, April 2022); (**b**) sheep resting in the shade of carob trees (Algarve, Portugal, October 2022); and (**c**) wool used as a soil mulch in a young carob orchard (Algarve, Portugal, July 2025).

6. Regulating Services

6.1. Microclimate Regulation

When considering the energy balance of an orchard, incoming radiation is dissipated through three main pathways: (i) latent heat flux (λE), the energy used for soil evaporation and leaf transpiration; (ii) sensible heat flux (H) associated with air heating and the consequent temperature increase; and (iii) soil heat flux (G), which represents the energy that heats the soil [37,38].

Orchard evapotranspiration is highly dependent on canopy size. When the leaf area index (LAI) is low, sparse canopy cover and minimal shading allow substantial radiation to reach the soil, while transpiration remains limited. Consequently, a large fraction of the available energy is dissipated as sensible heat (H), leading to a high Bowen ratio ($\beta = H/\lambda E$) [37].

In contrast, under a higher LAI (denser canopy), a greater proportion of incoming radiation is intercepted by the leaves. This increases transpiration due to a larger aggregate stomatal surface, while the increased shading reduces the energy reaching the soil, thereby limiting soil evaporation and sensible heat flux. This shift in energy partitioning results in a greater proportion of energy being used for latent heat flux (λE) and less for heating the air (H), causing the Bowen ratio to decrease. In other words, a higher leaf density in an orchard channels a greater proportion of solar energy into the biological process of transpiration, rather than dissipating it as sensible heat above the canopy [37].

Under well-watered conditions, trees can maintain high transpiration rates, dissipating a large proportion of available solar energy as latent heat, and cooling down the canopy below air temperature [112,113]. In irrigated orchards, increases in atmospheric evaporative demand (e.g., higher vapor pressure deficit) can enhance transpirational cooling by dissipating available energy as latent heat, thereby reducing the temperature of the canopy, surrounding air, and soil surface [112]. This effect occurs at the orchard level, resulting in differences in temperature between the orchard and adjacent areas [114]. By analogy, studies in urban areas demonstrated that irrigating green spaces can reduce mean air temperature by up to 2.3 °C and afternoon peaks by up to 4.2 °C, highlighting the profound capacity of irrigated vegetation to alter local microclimates [115].

Under water deficit, stomatal closure reduces transpiration, and less energy is dissipated as latent heat, causing the canopy to warm up, often above air temperature [112,113]. This frequently occurs in non-irrigated ecosystems such as forests and grasslands [112]. In orchards, the use of sprinklers is a strategy to artificially promote canopy cooling and simultaneously mitigate water deficit [116–118].

In young or sparse orchards, soil evaporation is a critical component of evapotranspiration (ET), contributing significantly to the total, especially after irrigation or rain [37]. Shortly after irrigation, soil evaporation is high and gradually decreases as the soil dries, becoming practically negligible in a very dry soil [119]. While localized irrigation creates wet patches that enhance evaporation, canopy development and increased shading eventually reduce their impact [37].

Irrigated orchards generally sustain high Leaf Area Index (LAI) values, and the continuous availability of water allows tree canopies to remain cool even under extremely high atmospheric temperatures [120]. This evaporative cooling effect benefits local fauna by creating favorable microhabitats for a wide range of animal species, including insects, birds, and mammals. Moreover, extensive areas of irrigated orchards contribute to thermal regulation at the landscape scale; by buffering peak temperatures, they provide important ecosystem services related to climate moderation and enhance human thermal comfort.

Globally, irrigation-induced cooling varies with the time of day, precipitation regime, and the balance between albedo and evapotranspiration, yielding an average annual daytime cooling of 0.96 ± 1.66 °C and a weaker nighttime effect of 0.34 ± 0.71 °C [121]. This cooling is particularly important in arid regions, where summertime reductions can reach 2.72 ± 1.71 °C under less than 400 mm precipitation, compared to negligible effects in humid regions (>1200 mm precipitation; 0.17 ± 0.47 °C) [121]. Despite reduced albedo from darker, wet soils, enhanced evapotranspiration and latent heat fluxes dominate, resulting in net cooling [121,122].

6.2. Carbon Sequestration and Storage

Carbon sequestration is a crucial regulating ecosystem service that removes atmospheric carbon dioxide (CO_2), thereby reducing its concentration in the atmosphere. CO_2 is a major greenhouse gas, and its increasing atmospheric concentration is a primary driver of global warming; consequently, enhancing carbon sequestration is essential for climate change mitigation [123,124]. Terrestrial ecosystems have two main carbon reservoirs: (i) plant biomass and (ii) soil [125,126]. In orchards, the plant biomass carbon pool includes both long-term carbon stored in perennial tree structures and more rapidly cycling carbon in herbaceous vegetation, which typically has an annual life cycle.

Carbon enters the agroecosystem primarily through photosynthesis. In this process, light energy drives the removal of electrons from water (H_2O), generating reducing power that is used to convert atmospheric CO_2 into carbohydrates. As a result of the splitting of water molecules, molecular oxygen (O_2) is released into the atmosphere as a by-product [127]. The carbohydrates produced through photosynthesis are subsequently used in a variety of plant biological functions. Notably, they serve as fundamental building blocks for the synthesis of structural molecules such as cellulose, hemicellulose, and—particularly in woody plants—lignin, thereby contributing to long-term carbon storage in plant biomass.

Carbon sequestration is closely linked to photosynthetic activity, which varies seasonally due to leaf development, phenology, and environmental factors such as radiation, temperature and humidity [128], with peak sequestration rates occurring during periods of rapid vegetative growth [129]. In evergreen crops, such as citrus, winter conditions promote stomatal closure, leading to reduced CO_2 assimilation and transpiration rates compared with warmer periods and, consequently, constraining CO_2 influx into the leaves [130,131]. Moreover, low temperatures downregulate the activity of enzymes involved in the Calvin–Benson cycle, including the CO_2-fixing enzyme, Ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), thereby decreasing the plant's capacity for CO_2 assimilation [132–134].

Higher planting densities reduce individual tree size, canopy development, and root system expansion due to increased inter-tree competition. However, this reduction is offset by the greater number of trees per unit area, resulting in comparable carbon sequestration at the orchard scale. Despite similar leaf area index (LAI) values across planting densities, denser orchards display a higher proportion of shaded foliage, which may influence leaf-level carbon content and overall carbon dynamics [135]. Under these conditions, long-term carbon storage is largely determined by the accumulation of permanent woody biomass, which represents a stable and substantial carbon reservoir in orchard systems [136].

Carbon storage in plant biomass varies among crops and is distributed across both above- and below-ground organs, with trunks and branches forming a major structural carbon pool that frequently accounts for more than 40% of the stored carbon [128]. Forest tree species generally allocate a higher proportion of biomass to aboveground organs [137]; in contrast, the canopy architecture of cultivated tree species is deliberately modified through management practices to enhance productivity and accommodate intensified fruit production [8,21,81]. Carbon stored in these trees tends to increase over time and eventually stabilize as they reach maturity [128]. Accordingly, carbon storage in orchard plant biomass is ultimately constrained by the maximum size attained by the trees.

Carbon is released from plant biomass through six main pathways: (i) cellular respiration; (ii) fruit harvest; (iii) leaf senescence and abscission; (iv) pruning operations; (v) root turnover; and (vi) root exudation.

To sustain metabolic processes, plants and other organisms within the agroecosystem oxidize carbohydrates through cellular respiration, during which chemical free energy is conserved in ATP and reduced electron carriers, with carbon returned to the atmosphere as CO_2 ($C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$).

Carbon contained in harvested fruits—comprising mainly carbohydrates such as sugars and structural polysaccharides, but also proteins, lipids and other compounds—can represent up to half of the carbon assimilated by trees through photosynthesis [128]. Carbohydrates are one of the three essential macronutrients in the human diet, and fruit consumption provides a valuable and healthy source of these compounds, as their high fiber content moderates sugar absorption, slowing it down. Consequently, although the carbon exported from orchards via harvested fruits is ultimately returned to the atmosphere, it plays a crucial role in ensuring food security, an important positive externality by orchard agroecosystems.

The remaining carbon-loss pathways—including leaf fall, pruning residues, root exudates, and root turnover—can contribute to soil carbon storage. The magnitude and persistence of this storage vary with environmental conditions and soil properties but are primarily governed by soil management practices [6]. Litter decomposition plays a central role in this process by supplying soil organic carbon and regulating nutrient cycling, with variations in decomposition exerting a strong influence on the overall soil carbon balance [138].

Once in the soil, dead plant biomass and root exudates are degraded by decomposer microorganisms, which break them down into simpler compounds used for cellular respiration. This is a key determinant of the carbon balance and varies with soil moisture and temperature [135]. Other intermediate organic compounds, not immediately used by microorganisms, can condense to form more complex and stable structures, eventually creating humus, a very stable form of organic carbon. Due to the accumulation of organic matter, soil is the largest carbon reservoir in terrestrial ecosystems [125,126,139]. Soil CO_2 emissions mainly result from biological respiration processes, including microbial decomposition of organic matter [140] and respiration by plant roots [141].

Irrigated orchards are specialized agroecosystems where strategic water application and concomitant fertilization mitigate growth-limiting stresses, thereby enhancing carbon storage potential compared to rainfed systems, particularly in intensive and super-intensive plantations [23]. Under rainfed conditions, severe summer soil water stress reduces stomatal conductance, severely limiting net CO_2 assimilation and causing pronounced midday and afternoon depressions in gas exchange [142,143]. In contrast, irrigation sustains the trees' water status, increasing transpiration, stomatal conductance, and stem water potential, significantly boosting photosynthetic activity [143,144]. Depending on the cultivar, irrigation can increase daily photosynthesis by 173% up to 331%, extending maximum carbon assimilation rates into hotter midday hours [145]. This increased biomass production directly enhances carbon inputs and, over time, substantially improves soil organic carbon (SOC) stocks—up to 100 cm depth—surpassing rainfed systems [22]. Consequently, super-intensive irrigated orchards can achieve remarkably positive net carbon balances, averaging up to 4.10 Mg C ha^{-1} yr^{-1} [23].

While this resource-rich environment stimulates overall carbon accumulation in biomass, soil, and litter (Figure 5), the net sequestration benefit must be balanced against the substantial carbon footprint of the manufacture and transport of fertilizers [22,23]. To optimize this balance, management practices such as reduced tillage, cover cropping, and the incorporation of organic composts or pruning residues are essential to minimize emissions and can even double the net carbon balance in these plantations [6,34,146–148]. Furthermore, irrigating with treated wastewater enables the utilization of dissolved nutrients, thereby lowering the fertilization carbon footprint and further reducing atmospheric carbon emissions [149].

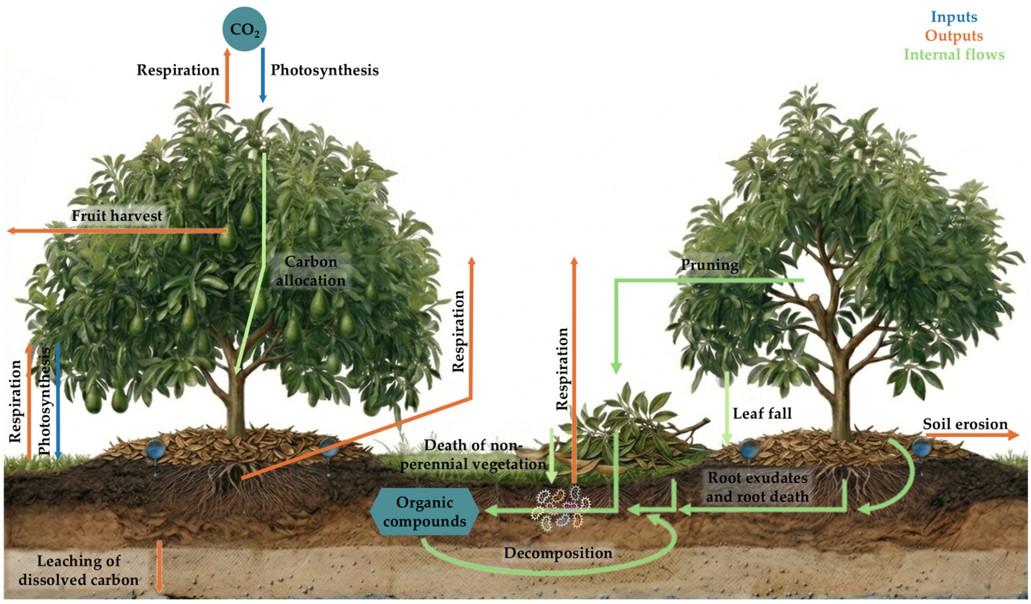


Figure 5. Carbon flows in the orchard. Inputs to the agroecosystem: uptake of atmospheric CO_2 through photosynthesis. Outputs from the agroecosystem: respiratory CO_2 emissions and carbon removal via fruit harvesting. Internal flows: redistribution of carbon between plant and soil compartments.

The incorporation of organic fertilizers can enhance soil organic carbon storage [150], increase the bioavailability of essential nutrients such as nitrogen and phosphorus, and improve the soil's water retention capacity [151], while also improving its structure [152].

Soil tillage leads to a reduction in soil organic carbon primarily due to three mechanisms: (i) soil aeration and enhanced microbial decomposition: tillage introduces oxygen into the surface soil layers, stimulating microbial activity and accelerating the breakdown of organic matter, resulting in increased CO_2 emissions; (ii) disruption of soil aggregates: tillage physically breaks down micro- and macro-aggregates that protect organic matter, thereby increasing its susceptibility to decomposition; and (iii) erosion: tilled soils, particularly on slopes or in semi-arid areas, are more prone to wind and water erosion, which remove organic-matter-rich soil particles [153]. Soil tillage and soil compaction contribute to reducing aggregate stability over time [154]. In orchard systems, soil management practices such as ground cover have been shown to promote substantially greater increases in soil organic carbon than tillage-based practices [6,155,156].

Although agricultural land expansion is frequently associated with carbon losses, particularly soil carbon release, the carbon and ecological outcomes of orchard establishment are highly context-dependent and critically influenced by prior land use, the degree of disturbance, subsequent management practices, and environmental conditions. Carbon flows in perennial crops differ from those in livestock systems and annual crops, mainly due to carbon storage in plant biomass and the continuous addition of organic matter to the soil, with minimal disturbance [157,158]. Additionally, technologies such as localized irrigation and fertilization allow orchards to be established in arid areas with naturally poor soils [159]. Sustainable soil management in orchards leads to a progressive increase in soil organic carbon over time [155,160], eventually reaching a maximum threshold that varies across systems. Studies have shown that the factor exerting the greatest influence on changes in soil organic carbon is temperature, explaining more than 50% of the variation, followed by crop age, and then by bulk density, clay content, and soil depth [160].

Several studies have shown that, in an agricultural context, orchard systems can serve as significant carbon sinks compared with other cropping systems, thereby contributing to atmospheric CO_2 mitigation while also meeting food-production objectives (Table 2).

Table 2. Examples of studies on carbon balances in orchards, carbon storage in tree biomass, and/or soil organic carbon.

Crop	Planting Density (trees ha^{-1})	Orchard Age	Carbon in Plant Biomass (kg tree^{-1})	Soil Organic Carbon (t ha^{-1})	Net Ecosystem Productivity (t ha^{-1})	Source
Citrus × sinensis 'Tarocco Sciré'	494	14	103.5	-	0.5	[135]
Citrus × sinensis 'Newhall'	1000	12	38.7	-	1.8	[135]
Citrus reticulata 'Clemenules'	500	12	56.2	-	10.4	[128]
Malus domestica 'Fuji'	3330	12	-	-	4.03	[161]
Corylus avellana 'Nocchione'	740	5	10.2	3.38 (0–30 cm)	-	[157]
Corylus avellana 'Tonda Gentile Romana'	625	50	40.2	11.2 (0–30 cm)	-	[157]
Prunus persica var. *nucipersica* 'Nectarlove'	571	7	-	$53_{(row)}$; $61_{(interrow)}$ (0–30 cm)	7.63	[158]

Up to this point, we have discussed how orchards remove atmospheric CO_2 through photosynthesis and store carbon in permanent plant biomass and soil pools. However, orchard maintenance practices also give rise to CO_2 and other greenhouse gas emissions, mainly associated with fertilization, soil management, phytosanitary treatments, and machinery operations. The magnitude of these emissions varies widely among crops and even among orchards of the same crop, being largely determined by management intensity and practice selection [158,162]. Consequently, organic orchards generally exhibit lower carbon footprints [162]. Nevertheless, evidence also shows that low-input management strategies for pesticide use, irrigation, and fertilization do not necessarily lead to significant changes in net ecosystem production or overall net ecosystem carbon balance [158].

6.3. Water Regulation

Irrigated orchards play a vital role in water regulation, acting as managed systems in which water cycles are shaped by the interaction between natural soil–plant processes and human-controlled water inputs (Figure 6). While these agroecosystems can enhance landscape resilience to hydrological extremes under climate change by influencing key processes such as water infiltration, soil moisture retention, evapotranspiration [163], and groundwater recharge, their net hydrological contribution is highly context-dependent and may involve important trade-offs. Indeed, the role of irrigated orchards in the water cycle varies significantly depending on multiple factors such as climatic conditions, soil properties, irrigation regimes, and seasonal dynamics.

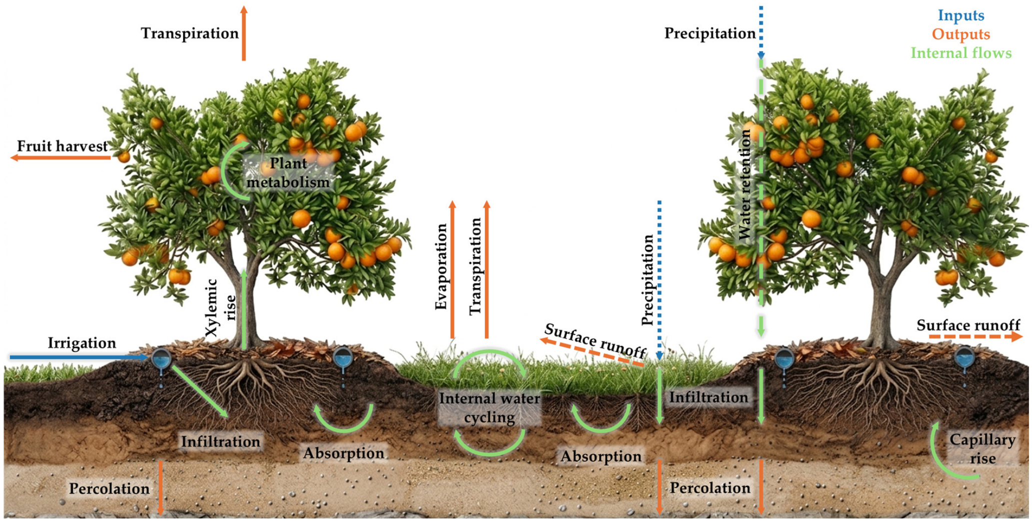


Figure 6. Water flows in an irrigated orchard. During periods of deficient precipitation, irrigated orchards receive supplemental water through irrigation systems. This enhances water availability for plant physiological processes, thereby increasing tree transpiration and crop yields. Both precipitation and irrigation can lead to water percolation into the subsoil; a fraction of this may subsequently rise via capillary action during the dry season, remaining available to both the trees and spontaneous vegetation.

During the rainy season, orchards contribute positively to water regulation by enhancing water retention and infiltration, often functioning in ways comparable to forest systems. Their root systems increase soil porosity and create preferential flow pathways, thereby promoting both infiltration and deeper percolation within the soil profile. During rainfall events, trees play a key role in modulating the water cycle. As observed in forested [164,165] and urban green spaces [166,167], canopy interception delays and reduces the transfer of precipitation to the soil surface, consequently minimizing surface runoff (Figure 6). In orchard systems, rainfall is partitioned into interception, throughfall, and stemflow, thereby regulating both the timing and spatial distribution of water inputs [168]. While throughfall delivers water to the soil in a heterogeneous pattern, stemflow concentrates water near the trunk, potentially creating localized zones of higher soil moisture [169]. As irrigated orchards frequently develop relatively large and dense canopies, characterized by a high leaf area index (LAI), rainfall interception is enhanced, amplifying these regulatory effects on soil water dynamics. However, increased interception may also reduce the effective amount of water reaching the soil, particularly in high-LAI systems, highlighting a potential trade-off between runoff reduction and net water availability. Moreover, part of the intercepted rainfall is stored on canopy surfaces and subsequently evaporated back to the atmosphere, linking hydrological regulation with the energy balance and contributing to microclimatic cooling [170,171].

At the landscape scale, orchards reduce surface runoff and increase water retention, helping to regulate water flow and maintain more stable water availability over time. This buffering effect is partly driven by canopy-mediated rainfall redistribution and delayed water inputs into the soil, which help attenuate peak flow events [172,173]. This is especially important in low-lying coastal areas, where surrounding orchards or forested uplands can reduce downstream flood risk by slowing and absorbing excess water compared with non-vegetated landscapes. In addition, the deep root systems of perennial crops can substantially modify hydrological processes beyond the surface soil layer, influencing the vertical redistribution of water, water storage in deep soil layers, and groundwater recharge dynamics. Using stable isotopes ($\delta^{18}O$ and $\delta^{2}H$) and tritium profiles, a study conducted in the North China Plain [174] demonstrated that deep soil water recharge is largely associated with heavy precipitation events, particularly during the monsoon season. Furthermore, the relatively homogeneous isotopic composition below a depth of 6 m indicates long-term storage and slow vertical redistribution of infiltrated water [175–177]. The authors further noted that deep-rooted orchards (pear) promoted greater water storage in the deep soil compared to shallow-rooted agricultural systems (maize) under irrigated conditions, indicating that perennial orchard systems may facilitate deeper infiltration pathways and long-term water retention in the soil profile. However, the same study highlighted significant hydrological trade-offs associated with orchard systems. Although orchards can increase deep infiltration and the redistribution of water in the soil, they also exhibited evapotranspiration rates substantially higher than those of annual crops, with evapotranspiration accounting for up to 95.7% of total annual water inflows in older pear orchards. This indicates that a large proportion of incoming water is returned to the atmosphere rather than contributing to groundwater recharge. This high-water consumption was associated with increased water uptake by roots and the progressive development of deeper root systems as the orchard aged, resulting in greater soil water deficits and reduced deep drainage [178]. Furthermore, the lower albedo of the land surface and the higher LAI of the orchards altered the surface energy balance and evapotranspiration dynamics, reinforcing the role of perennial orchards as strong eco-hydrological modifiers. Overall, these findings demonstrate that the hydrological impacts of orchards are highly context-dependent and may involve trade-offs between water regulation, groundwater recharge, and atmospheric water fluxes, emphasizing the need to integrate hydrological considerations into large-scale land-use planning in water-scarce regions.

In contrast, during the dry season, irrigated orchards rely on stored surface water (e.g., reservoirs and dams) or groundwater, when water resources are naturally more limited. In this period, water output from the system occurs mainly through evaporation, plant transpiration, and export via harvested biomass. In addition, tree canopies reduce soil temperature and incoming solar radiation at the soil surface, limiting evaporative losses. Consequently, irrigated orchards help maintain higher soil moisture levels by both introducing water into the system and limiting evaporation [179], thereby reinforcing their role as regulators of water availability under dry conditions.

Yet, the effectiveness of irrigation in regulating water dynamics is strongly dependent on management practices. While inappropriate irrigation management may lead to deep percolation, representing a loss for immediate crop water use but supporting groundwater recharge, biophysical trade-offs often emerge between provisioning and regulating ecosystem services. In particular, the increase in tree biomass and the LAI, stimulated by the inflow of water and nutrients, maximizes carbon sequestration and fruit production, but can simultaneously result in a decline in groundwater conservation indicators and in an increased risk of nitrate leaching through drainage [24]. Consequently, the transport of agrochemicals in percolated water can lead to diffuse pollution and soil salinization, posing risks to both water quality and soil health [180,181]. On the other hand, orchards can be irrigated with treated wastewater, thereby conserving potable water resources and acting as a biological filter when this water percolates through the soil, while also allowing the recovery of dissolved nutrients [149], which, if discharged into the environment, would otherwise be considered pollutants.

In this context, irrigation efficiency becomes a key consideration and can be approached from two complementary perspectives. From a productivity standpoint, water use efficiency (WUE) is commonly defined as the amount of fruit produced per unit of water applied. In regions where water is a limited resource, currently used irrigation systems are already relatively efficient, particularly localized systems such as drip irrigation [182]. However, to achieve higher WUE, it is also necessary to adopt strategies that reduce water inputs while maintaining fruit yield and quality. One such approach is regulated deficit irrigation, which allows for reduced water application during specific phenological stages without significantly affecting production. On the other hand, from an ecosystem services perspective, reduced water inputs may also limit water availability within the agroecosystem, potentially influencing soil processes, microclimatic regulation, and biodiversity, thus highlighting trade-offs between water saving and ecosystem functioning.

The capacity of soil to receive, store, and supply water is largely determined by soil physical and chemical properties, particularly those related to structure and soil organic matter (SOM) content, which directly influence infiltration and water retention processes. Soils with higher organic matter content and better aggregation generally exhibit greater water-holding capacity and enhanced infiltration dynamics. The presence of herbaceous soil cover enhances these processes by reducing runoff velocity, increasing infiltration, and protecting the soil surface from water erosion [183]. Conversely, systems with a high proportion of bare soil are more prone to water losses, erosion, and reduced soil moisture [184]. The same applies in non-cultivated, degraded, or rainfed systems. Here, rainfall often results in rapid surface runoff due to limited infiltration capacity, thereby reducing groundwater recharge.

Therefore, optimized irrigation strategies, together with the inherent advantages of permanent crops and their associated soil management practices, are key to regulating surface water dynamics, increasing water use efficiency, and minimizing environmental risks.

6.4. Soil Erosion Control

Soil erosion has emerged as a critical global concern, driven by decades of continuous soil degradation and intensified by inappropriate agricultural practices [48,49]. Since soil is effectively non-renewable on human timescales, current erosion rates in Europe, ranging from 3 to 40 Mg ha^{-1} $year^{-1}$ [185], severely threaten the goal of increasing agricultural productivity to meet rising food demand [185,186]. This degradation is particularly severe in soils with low organic matter and weak structural stability [187,188], where runoff transports nutrients and valuable soil biota off-site [189]. Historically, soils under annual crops have shown higher vulnerability to these processes due to frequent soil disturbance and limited vegetation cover [190].

In contrast, orchards are perennial agroecosystems that inherently offer superior erosion control. Even in the absence of ground cover, the tree canopy provides a first line of protection by intercepting rainfall, thereby reducing raindrop kinetic energy at the soil surface [191]. However, irrigated orchards are particularly effective at mitigating soil loss, as the consistent availability of water allows for the maintenance of larger, denser canopies, thereby enhancing rainfall interception. Proper management within these systems significantly enhances soil conservation. The use of frequent tillage and herbicides on steep slopes has historically accelerated degradation [192,193], whereas the preservation of spontaneous vegetation or cover crops provides the mechanical protection necessary to promote infiltration and mitigate both splash and concentrated flow erosion [32,49,194].

Empirical evidence from citrus orchards demonstrates that groundcover can markedly reduce runoff and soil loss by 46.9% and 66.8%, respectively, compared to bare-soil management [192]. Long-term watershed studies (1957–2013) show that converting annual cropland to permanent plantations reduces erosion intensity, with arable land previously exhibiting rates 9.6 times higher than permanent crops, lowering basin sediment loss from high to moderate [195]. Herbicide use, which leaves orchard soil bare, produced the highest slope-scale erosion rates (11.3 Mg ha^{-1} yr^{-1}), whereas inter-row ground cover reduced erosion by up to 99%, nearly eliminating soil loss [196]. Beyond living cover, the integration of mulching and the incorporation of shredded pruning residues improves soil porosity and aggregate stability, effectively dissipating runoff energy [197,198]. These practices establish a clear management efficiency gradient: while bare land and traditional tillage lead to peak erosion risk, the transition to grass cover and heterogeneous vegetation significantly stabilizes the ecosystem [199,200]. Consequently, in particularly vulnerable areas, such as those with gypsiferous soils, site-specific groundcover strategies are essential to prevent erosion risks [201]. Conversely, frequent soil tillage in olive groves (4–5 times per year) resulted in severe soil loss, reaching 29.4 Mg ha^{-1} yr^{-1}. Although the tree canopy provided about 38% ground cover against raindrop impact, the remaining 62% of bare soil and machinery-induced furrows largely offset its protective effect [202]. Ultimately, through the combination of canopy interception, reduced tillage, and permanent groundcover, irrigated orchards serve as key providers of soil erosion control as a regulating ecosystem service [32–34].

6.5. Wildfire Spread Control

Fire-prone areas such as the Mediterranean face persistent risks of human, ecological, and economic losses from wildfires. However, ecosystem services related to fire regulation are rarely quantified and are often omitted from socio-ecological and economic assessments of land use [203]. Certain forms of agricultural land use can nevertheless provide effective fire-regulating services.

While some studies suggest that biomass in orchards, particularly non-irrigated ones in arid regions, may increase fire hazard [204], irrigated orchards demonstrate the opposite effect. Irrigation induces a significant cooling effect, reducing land surface temperature by up to 1.22 °C [205]. When irrigation is widespread, this cooling effect can extend beyond the plot scale and manifest at the landscape to regional level, as increased evapotranspiration alters surface energy partitioning, potentially lowering fire risk. More importantly, live fuel moisture content, the key determinant of fire susceptibility [206], remains high in these agroecosystems due to increased root-zone volumetric water content [207]. As a result, large-scale wildfires, upon reaching irrigated orchards, may scorch the perimeter trees but typically fail to propagate through the entire irrigated area (Figure 7). Similar fire-mitigation effects have also been observed in other irrigated land uses, such as golf courses and irrigated shrublands, where irrigation consistently reduces fire intensity and spread compared to non-irrigated vegetation [39,40].

Figure 7. Wildfire perimeter at an irrigated orchard following the August 2021 wildfire in eastern Algarve (Castro Marim, Portugal). The fire, which spread over several tens of kilometers through forested, agricultural, and urban areas, was halted upon reaching a mosaic of irrigated orchards. Perimeter lemon trees were scorched but did not ignite, and a similar effect was observed in avocado trees adjacent to the burned area.

Several wildfires in the Algarve region (Portugal) ceased to spread after reaching irrigated orchards (Figure 8). This effect is likely linked to increased landscape patchiness, lower orchard microclimate temperatures, and higher plant biomass moisture compared to surrounding non-irrigated land uses.

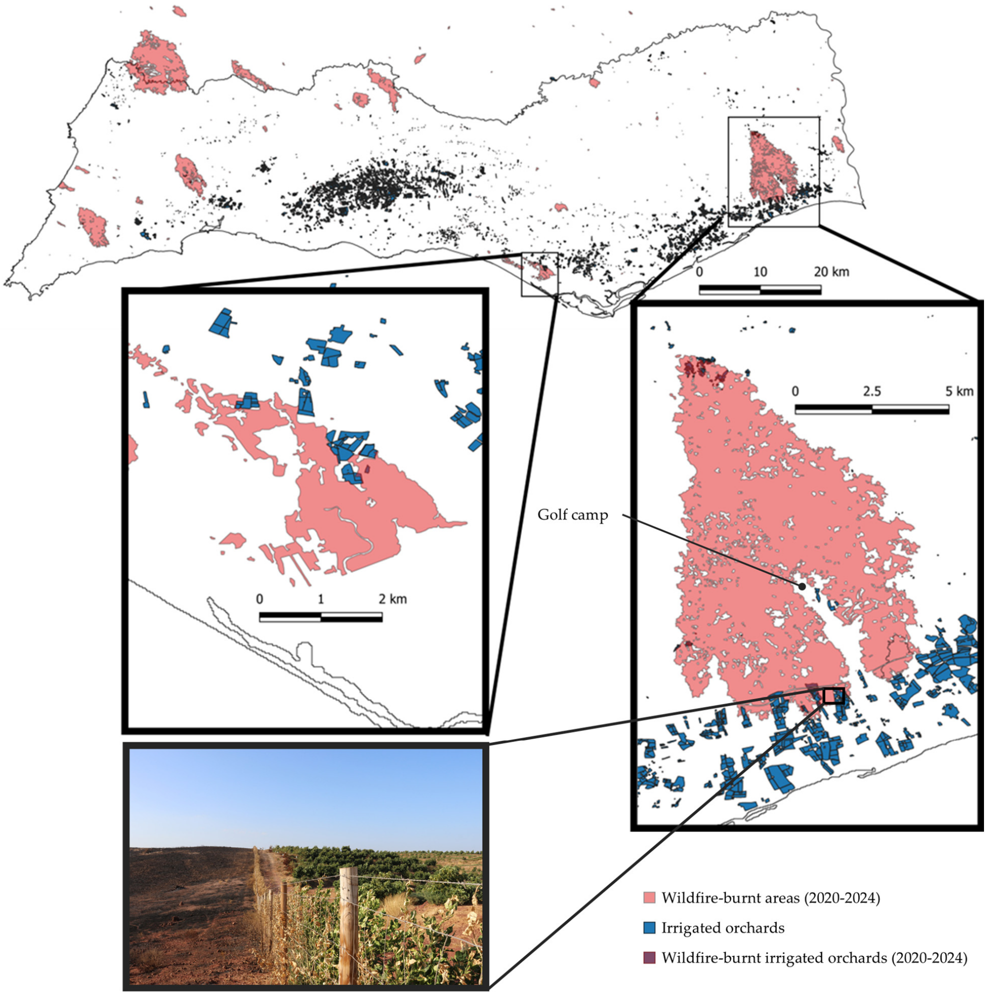


Figure 8. Wildfires and irrigated orchards in the Algarve region (Portugal). Red polygons represent wildfire-burnt areas between 2020 and 2024, while blue polygons indicate irrigated orchards. Burnt

area data were obtained from the Instituto da Conservação da Natureza e das Florestas (ICNF), *Territórios Ardidos dataset*, including annual shapefiles for 2020–2024 (https://si.icnf.pt/shp/ardida_2020 to https://si.icnf.pt/shp/ardida_2024 accessed on 13 November 2025). Data on irrigated orchards were retrieved from the Instituto de Financiamento da Agricultura e Pescas (IFAP), WMS service "Parcelas, ocupações de solo e culturas" (https://www.ifap.pt/isip/ows/isip.data/wms accessed on 26 November 2025). The base map of the Algarve region was obtained from *Mapa dos Distritos*, Agência para a Reforma Tecnológica do Estado (https://dados.gov.pt/api/1/datasets/r/d57a2fd1-0a5b-43a2-bbd1-27f6cbcb5c48 accessed on 11 November 2025).

Irrigated orchards can slow fire spread, protecting plantation structure and economic returns while also acting as strategic firebreaks for nearby infrastructure (Figure S1) and natural areas. Although shredded pruning residues in inter-rows may allow some fire movement (Figure S2), orchards may still reduce fire intensity and propagation. In burned landscapes, these orchards become key green refuges that support wildlife, as seen in the high bird activity observed after fire events (Video S1). This effect also preserves the soil microbiota and critical below-ground ecosystem functions from thermal degradation [208].

7. Cultural Services

7.1. Landscape

Landscape is defined by the European Landscape Convention as "*an area, as perceived by people, whose character is the result of the action and interaction of natural and/or human factors*" [209]. This definition explicitly highlights the central role of human activities in shaping landscapes, with agriculture being one of the main drivers of this long-term transformation [210].

The continuity of landscapes is strongly connected to the values attributed to them by society [211]. While rapidly changing areas struggle to establish a recognizable identity [212], traditional and enduring landscapes tend to be appreciated and cherished by communities [213,214].

Orchards contribute decisively to the visual structure and cultural significance of many rural landscapes, frequently acting as defining elements of territorial identity [17,56–58]. As perennial cultivation systems, orchards embody long-term interactions between people and land, incorporating accumulated knowledge, management traditions and place-based practices. Consequently, these environments are increasingly recognized as 'food landscapes': spatial configurations where aesthetic quality, cultural memory, and food production converge to strengthen a community's sense of belonging [215].

From an aesthetic and perceptual perspective, cultivated orchard landscapes are frequently characterized by high visual quality. Regular planting patterns, terraced landforms, and marked seasonal dynamics associated with flowering and fruiting enhance landscape diversity, structural complexity, and scenic value [17,216]. Historically, fruit tree cultivation has transformed landscapes through features such as terraced slopes, step balks, and stone banks, creating distinctive landscapes closely linked to regional historical development (Figure S3) and adaptive agricultural strategies [17]. However, declining economic viability often leads to orchard abandonment, resulting in the progressive loss of the unique cultural landscapes they generate (Figure S4) [20]. A striking example of this process is the decline of traditional almond groves in the Algarve (Portugal). Integrated into Mediterranean dryland agroecosystems for centuries, almond trees shaped the region's cultural identity and achieved international recognition for their seasonal flowering landscapes before widespread abandonment began in the 1960s. Recently, however, new irrigated almond orchards have been established. These economically viable orchards are beginning to restore the iconic "snow-covered" appearance of the southern Portuguese landscape, evoking imagery of snowy fields in a subtropical region where snowfall is absent.

Mediterranean citrus orchards illustrate particularly well how irrigated orchards shape landscapes of high cultural and aesthetic value, in some cases formally recognized by UNESCO. The terraced lemon orchards of the Amalfi Coast reflect centuries of adaptation to steep terrain, integrating irrigated agriculture and architecture into a distinctive Mediterranean cultural landscape [217,218]. Similarly, the irrigated citrus orchards of *La Huerta de Valencia* exemplify traditional water-management systems and horticultural practices, that express enduring socio-ecological values of Mediterranean irrigated agriculture [219–221]. Irrigated orchard landscapes of high cultural relevance are also found in other regions of the world. In California's Central Valley, extensive almond and citrus orchards have become emblematic features of the regional landscape, reflecting the historical development of large-scale irrigation infrastructure and shaping contemporary perceptions of agricultural productivity and rural space. These productive environments function as dynamic food landscapes, where the visual identity of the territory is a direct expression of its role in food systems. In North Africa and the Middle East, irrigated date-palm orchards within traditional oasis systems constitute iconic cultural landscapes, where water management, food production, and settlement patterns are deeply intertwined. In East Asia, long-established irrigated pear and peach orchards in parts of China and Japan similarly contribute to rural identity through their seasonal visual expression and long-standing cultivation traditions. Beyond these more emblematic examples, irrigated orchards also contribute to landscape quality in many other contexts, enhancing visual amenity by breaking spatial monotony and, in some cases, being the only landscape elements that retain intense greenness during prolonged dry periods.

7.2. Cultural, Historical, and Traditional Values

In some regions, the cultivation of specific crops is integral to local identity and traditional values, with agricultural practices transmitted across generations and shaping local ways of life. Fruit production often extends beyond economic activity to express cultural identity, fostering strong connections between farmers and the environment and reinforcing community belonging and collective memory [215].

Extensive orchards are often closely linked to regional and local identity, embedded in rural cultural traditions and associated with local varieties and traditional products [222]. Their terminology and practices reflect knowledge transmitted across generations [57]. In some cases, they also preserve historical identity and collective memory of traditional agricultural organization, contributing to cultural landscapes and historical land-use patterns [17,57].

The Mediterranean diet, renowned for its positive health effects and historically shaped by the populations of the Mediterranean Basin, is characterized by a high consumption of fruits, eaten both as fresh produce and as processed products [223]. In current Mediterranean agri-food systems, a substantial share of this fruit production—particularly under modern conditions—is derived from irrigated orchards. This is especially the case for species (or groups of species) such as citrus fruits, figs, pomegranates, almonds, stone fruits (including peaches, apricots, cherries and plums), pomaceous fruits (apples, pears and quinces), as well as carobs, loquats, walnuts and pistachios [224–227].

7.3. Recreation and Tourism

In regions where the cultivation of a specific crop is deeply embedded in local culture and traditional values, it is common for festivals and recreational activities to be associated with the agricultural cycle [228–231]. These festivals often include activities that combine leisure, learning, and sensory engagement, such as visiting orchards, picking fruits, or participating in food-related workshops [232]. Gastronomic festivals offer a recreational platform where tasting and exploring local fruits entertains and educates visitors about production processes, seasonality, and fruit quality [233–236]. These also reinforce regional gastronomic identity and promote local fruits through tastings and direct sales [232]. The produce of irrigated orchards frequently serves as the centerpiece for cultural events attracting thousands of tourists. Prominent examples (cited in their original names) include: *Fête du Citron* (Menton, France); *Fira de la Taronja* (Sóller, Mallorca, Spain); *Battaglia delle Arance* (Ivrea, Italy); *Silves, Capital da Laranja* (Silves, Portugal); *International Mango Festival* (Delhi, India); *Mandorlo in Fiore* (Agrigento, Sicily, Italy); *Fiesta del Almendro en Flor* (Gran Canaria, Spain); *Festival des Amandiers* (Tafraout, Morocco); *Festival-e Pesteh* (Kerman, Iran); *California Walnut Festival* (California, United States); *Apple Blossom Festival* (Shenandoah Valley, United States); *Fête de la Pomme* (Normandy, France); *Festa dell'Olio Nuovo* (various regions of Italy); and *Fiestas del Aceite* (Andalusia, Spain).

The combination of recreation and local fruit production provides multiple benefits: (i) economic—direct fruit sales at festivals, increased restaurant revenue from fruit-based dishes, and higher hotel occupancy [237,238]; (ii) social and cultural—promotion of local culinary heritage, strengthening of community identity, and visitor education on agricultural practices [236,239]; and (iii) tourism and branding—enhancement of the destination's image, encouragement to repeat visits, and provision of unique experiences centered on local produce [238,240].

In this context, orchard-dominated landscapes support tourism by stimulating recreational activities and enhancing regional attractiveness. Beyond their visual appeal, certain fruit species offer a unique sensory experience during flowering due to their intense fragrance. A prime example is found in citrus orchards, where the orange blossom scent, a result of the high essential oil content in the flowers [89], is so iconic that it defines the identity of entire tourist regions. This is the case of the Costa del Azahar (Orange Blossom Coast), where the fragrance (known as *azahar*) creates a distinct olfactory landscape that significantly increases visitor interest and regional prestige. They can also directly generate agrotourism, which integrates agricultural production with visitor experiences [59,60]. This approach attracts individuals interested in nature, culture, and leisure, while providing farmers with additional income beyond crop sales [60]. Agrotourism in orchards offers visitors experiences of local lifestyles and culture, including harvesting, tasting, artisanal products, educational activities, tours, festivals, and gastronomy [60,241,242]. Studies indicate that the most preferred activities are harvesting and tasting, orchard walks, learning about agricultural tourism, cycling, and engaging with farmers' lifestyles [60].

8. Supporting Services

8.1. Nutrient Cycling

Nutrient cycling in soil refers to the biogeochemical processes by which plant nutrients, such as nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur, are released, transformed, taken up, and recycled within the soil ecosystem [243]. Nutrient cycling occurs in five stages: (i) input of organic matter and nutrients through litterfall, dead roots, other organic residues, and external additions such as fertilizers and amendments onto the soil; (ii) decomposition of organic materials by soil microorganisms; (iii) mineralization of organic forms into inorganic forms such as nitrates, phosphates, and sulfates; (iv) plant uptake of nutrients in their available inorganic forms from the soil solution; and (v) return of nutrients to the soil through tissue death and subsequent deposition.

The rate and efficiency of nutrient cycling are strongly influenced by environmental, biological and orchard management factors, with soil microbial activity playing an important role across all systems. In tropical climates, decomposition rates are typically higher during the rainy season, due to favorable moisture and temperature conditions that enhance microbial activity, resulting in more efficient nutrient cycling compared with degraded areas [244]. Nutrient losses may occur through leaching, erosion, and volatilization [31]. In orchards, most nutrients are recycled back into the soil through processes such as leaf litterfall and root turnover [31].

Nutrient cycling therefore relies on both the continuous input of plant residues from the crop into the soil [244] and the presence and activity of soil microbial communities [245]. Soil bacterial and protist diversity plays a crucial role in the biogeochemical cycling of multiple nutrients, whereas fungal diversity appears to exert a comparatively smaller influence on these processes [246]. Nutrient cycling is also strongly affected by the rate and quality of litter production. In the Amazon region, litter from mango orchards has been shown to contain higher nitrogen, calcium, and magnesium concentrations than litter from degraded areas, with nutrient levels comparable to those of native forests [244].

Soil management strongly affects nutrient cycling. Compost application can stimulate soil food webs; however, different compost types shape distinct microbial communities, altering trophic interactions and potentially enhancing plant nutrient uptake [245]. In orchards, pruning residues should be shredded and retained in inter-row areas, when phytosanitary conditions allow, to minimize nutrient export and promote internal nutrient recycling [31].

The establishment of cover crops in orchard inter-rows, particularly legume-based mixtures, enhances soil nutrient cycling and promotes beneficial shifts in soil microbiome composition [247,248]. These cover crops increase nitrogen (N) availability and can also elevate potassium (K) and boron (B) levels while reducing calcium (Ca) and manganese (Mn) availability, likely as a result of organic matter mineralization, gradual nutrient release, and changes in soil chemistry [248]. Residue incorporation further supports nutrient release and tree uptake, highlighting the role of legumes as green manure in promoting sustainable biological nutrient recycling [247,248]. Compared with other cover crops, legumes are associated with more substantial changes in the soil microbiome, including increases in beneficial microorganisms and reductions in soil-borne pathogens, although these responses are modulated by plant density, species composition, relative proportions, and abiotic soil conditions [247].

Inoculation with arbuscular mycorrhizal fungi enhances nutrient cycling by increasing soil NH_4^+, NO_3^-, available phosphorus, and exchangeable potassium. It also stimulates microbial biomass and enzymatic activity, accelerating organic matter decomposition and C and N cycling, while promoting microbial diversity and beneficial taxa such as *Bradyrhizobium* and *Nitrospira*, thereby improving overall nutrient cycling efficiency [249].

8.2. Biodiversity

Agriculture has long been recognized as a major driver of biodiversity loss, especially under intensive or poorly managed systems that simplify landscapes and restrict conservation practices, thereby reducing species diversity and abundance [250]. The impact of agriculture on biodiversity loss was vividly illustrated in Rachel Carson's *Silent Spring* [251], which documented the ecological consequences of chemically intensive farming in the United States during the post-Green Revolution era. This period was shaped by productivist paradigms that prioritized yield maximization, often at the expense of ecological integrity, and that still persist in some agricultural contexts. By contrast, many modern orchards managed using diversified, low-input or agroecological practices are no longer "silent", instead supporting a wide range of insects, birds, and other fauna. These systems increasingly highlight the potential role of orchards to conserve biodiversity within broader agricultural landscapes.

To some extent, biodiversity loss is an inherent consequence of food production, a process that has existed, albeit at much smaller spatial and technological scales, since the advent of agriculture approximately 12,000 years ago [252], with the establishment of early orchards about 8000 years ago [17]. Agriculture footprint remained relatively limited until the post-Green Revolution era, when landscape simplification and increasingly input-intensive management led to pronounced declines in farmland biodiversity and associated ecosystem services [253,254]. The resulting challenge is to reconcile food production with environmental sustainability through context-specific management strategies adapted to different crops and regions. Agriculture has repeatedly demonstrated its potential to severely harm global biodiversity, particularly when it involves deforestation and species extinction [255], the expansion of large-scale monocultures that reduce landscape heterogeneity and simplify habitats [50,51], and the widespread use of chemical inputs [256] with few or even no practices that support biodiversity conservation [250]. However, agriculture can positively contribute to biodiversity by reclaiming degraded lands, providing resources and habitats for a wide range of organisms [257–259], including rare or endangered species, and functioning as green corridors within fragmented landscapes [260]. Increasingly, farmers and policymakers recognize that biodiversity loss can ultimately reduce yields and increase production costs, whereas greater spatial heterogeneity and ecological diversification can generate win–win outcomes for both agricultural productivity and biodiversity conservation [261].

Irrigated orchards can represent structurally complex agroecosystems with multiple strata that produce various resources and fulfil the habitat requirements of many species, including plants, microorganisms, and fauna, and their interactions.

In orchards, plants typically form at least two strata: (i) an arboreal stratum; and (ii) an herbaceous stratum (Figure 9). The arboreal layer generally comprises two biological components: the cultivar and the rootstock. The use of traditional cultivars contributes to the conservation of genetic resources and is closely linked to cultural ecosystem services [262]. The herbaceous layer, which is commonly present, may consist of spontaneous species or be intentionally established as cover-crops, thereby increasing biodiversity even in high-intensity agroecosystems [263].

Figure 9. Plant diversity in an avocado (*Persea americana*) orchard, including spontaneous vegetation from the following families: Papaveraceae, Fabaceae, Poaceae, Asteraceae, Brassicaceae, Malvaceae, Plantaginaceae, among others (Algarve, Portugal, May 2020).

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In agroecosystems, microorganisms are fundamental to the ecosystem services the agroecosystem provides, as they play key roles in nutrient cycling [245] and in the carbon cycle [264], enhance plant nutrient uptake (e.g., through mycorrhizal associations) [249], and contribute to the biological control of pathogenic organisms [265,266]. In irrigated orchards, soil management practices strongly influence the soil environment and, consequently, soil microbiota, since soil moisture is a major driver of microbial activity and nutrient cycling. Irrigation in orchards generally increases microbial biomass and activity [267,268]. Moreover, higher soil microbial diversity is associated with enhanced ecosystem stability and resilience, reducing susceptibility to both anthropogenic and natural stresses [269].

Regarding animals, the most common groups found in orchards are arthropods, small mammals and birds. Arthropods, the most species-rich animal phylum, serve as key bioindicators and play fundamental roles in structuring ecosystems and supporting species persistence in both natural and agricultural systems [255,270]. Orchard management strongly influences agrosystem equilibrium. When this balance is disrupted, some arthropod species may proliferate excessively and become agricultural pests. Such imbalances often arise from high food availability, high reproductive rates, and reduced natural mortality, leading to population outbreaks that cause economic damage, yield losses and broader socioeconomic and environmental impacts [271,272]. In contrast, when agroecosystem equilibrium is maintained, orchards support a substantial proportion of beneficial arthropods (Figure 10) that provide essential ecosystem services, including pollination, contributions to nutrient cycling, and the regulation of other arthropod populations [273]. These services enhance crop productivity and resilience while reducing reliance on external agricultural inputs, thereby supporting the long-term sustainability of agroecosystems.

(a) (b) (c)

Figure 10. Examples of pest–natural enemy dynamics on young shoots of 'Nadorcott' mandarin: (**a**) mummified aphid resulting from parasitoid activity; (**b**) larva of Coccinellidae preying on an aphid; (**c**) eggs of Coccinellidae.

Increasing ecological complexity in intensive orchards enhances arthropod abundance and diversity, including pollinators and natural enemies, indicating that well-managed systems can mitigate impacts and support biodiversity [35,36]. A key ecosystem service is the biological control of arthropod populations by predators and parasitoids, which helps suppress pest outbreaks. However, the effectiveness of this service depends on ecological complexity and varies with spatial scale, landscape context, and the availability of surrounding natural or semi-natural habitats [35,274,275].

In orchards, landscape heterogeneity can be enhanced through the conservation of semi-natural habitats, such as ecological refuges, which increase species abundance and richness and support a wide range of ecosystem services [276–278]. Orchards with heterogeneous structures, combining trees, grasslands and adjacent arable land, tend to support high levels of biodiversity by enhancing floristic diversity and functioning as ecological cor-

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ridors and refuges for rare and disturbance-sensitive species [17]. By acting as transitional habitats within agricultural landscapes, these systems promote the diversity of multiple taxonomic groups, including birds, pollinators (e.g., bees, flies, and some wasps), beetles, butterflies, terrestrial gastropods, and plants [216].

Irrigation can alter arthropod communities by modifying vegetation structure and microclimate, although effects are inconsistent and often depend on broader management practices such as pesticide use and ground cover management [279,280]. In drought-prone environments, water limitation constrains both production and biological communities, whereas irrigation can reduce stress by increasing resource availability and soil moisture. Higher moisture levels are associated with increased arthropod abundance, including beetles and spiders, underscoring the role of microclimatic conditions in shaping these communities [281–283]. Beyond supporting arthropods, orchards can also serve as habitats for macrofauna, such as small mammals and birds, which may complete part or all of their life cycles within agroecosystems (Figure 11a). In Mediterranean and other dryland regions, orchards often provide relatively stable, resource-rich environments compared with non-cultivated or degraded lands; however, the loss of traditional tree–grassland mosaics in these landscapes can contribute to declines in species that depend on heterogeneous habitats [284,285].

(a) (b) (c) (d)

Figure 11. Examples of macrofauna frequently found in irrigated orchards in the Mediterranean Basin: (**a**) a nest of a common blackbird (*Turdus merula)* in the canopy of an avocado tree (Algarve, Portugal, March 2023); (**b**) red-legged partridge (*Alectoris rufa*) sheltering in an avocado orchard (Algarve, Portugal, February 2026); (**c**) red fox (*Vulpes vulpes*) in a persimmon orchard (Algarve, Portugal, March 2026); and (**d**) a common chameleon (*Chamaeleo chamaeleon*) sheltering in an orange orchard (Algarve, Portugal, October 2011).

Structural heterogeneity in orchards, including tree canopies, herbaceous understory vegetation, and leaf litter, is essential for maintaining high levels of biodiversity [108]. This structural complexity provides shelter, nesting sites, and foraging resources while also buffering organisms against climatic extremes. Increased microhabitat complexity, especially when bare soil is reduced, is further associated with higher abundance and species richness of small mammals [286,287]. Leaf litter layers create suitable microenvironments for macroinvertebrates [288] such as earthworms, millipedes, and other taxa [289], which are an important food resource for small mammals [290]. In turn, small mammals play a pivotal role in ecosystem functioning by contributing to soil aeration, regulating weed populations, and supporting biological control [291–294].

Trees play a critical role in moderating microclimatic conditions, especially during the summer, by reducing heat stress and buffering temperature extremes [295,296]. Irrigation further enhances understory development in orchards, increasing food availability both directly (through greater plant biomass and seed production) and indirectly by supporting higher insect abundance. These conditions benefit numerous species, including the European rabbit (*Oryctolagus cuniculus*) and ground-nesting birds such as the Red-legged partridge (*Alectoris rufa*) (Figure 11b), which benefit from the combined availability of cover, food resources, and relatively low disturbance. During periods of seasonal resource limitation, irrigated orchards can also enhance landscape connectivity by facilitating species movement across fragmented habitats, thereby supporting the persistence of diverse faunal communities, including predators (Figure 11c). Consequently, orchards may function as suitable habitats for breeding, foraging, and refuge, contributing to the maintenance of local populations [297]. Promoting the activity of pest predators (e.g., *Pipistrellus kuhlii* preying on *Prays oleae* in olive groves) may yield significant economic benefits [298,299]. In some cases, water sources can be installed for wildlife to prevent damage to irrigation systems caused by animals seeking water (Figure S5). In addition, the managed nature of these ecosystems generally reduces wildfire risk compared to unmanaged landscapes, further enhancing habitat stability.

Habitat provision in orchards is an important supporting ecosystem service, but its effectiveness is strongly shaped by management intensity [300]. Intensive practices such as frequent soil disturbance, herbicide use, and reduced ground cover can limit habitat availability and diversity of resources, thereby disrupting trophic interactions and ecological functioning. In contrast, low-input orchards characterized by greater structural complexity and less disturbance generally sustain higher biodiversity and more stable biological communities. Such systems may even provide suitable habitat for strictly protected species such as the common chameleon (*Chamaeleo chamaeleon*) (Figure 11d), a species commonly associated with Mediterranean ecosystems, such as shrublands, coastal vegetation and orchards [301]. Nevertheless, sustainability outcomes are context-dependent, and in some cases higher-intensity agricultural systems may reduce pressure on surrounding natural ecosystems, for example by limiting land conversion. Optimizing ecosystem service provision therefore requires the integration of local and landscape-scale management strategies, as well as a clearer understanding of their relative contributions to biodiversity conservation and long-term sustainability [253].

8.3. Pollination

Pollination is a fundamental ecosystem service that directly influences crop yield, fruit quality, and farm economic viability, playing a key role in food security, while also being essential for the reproduction of numerous spontaneous plant species. It occurs through abiotic vectors, such as wind (anemophily) and water (hydrophily), or through biotic agents, including birds (ornithophily), bats (chiropterophily), and insects (entomophily) [302]. Many irrigated orchards rely on effective pollination to sustain productive performance and, through appropriate management, contribute to maintaining pollination as an ecosystem service.

Although wind pollination is relevant for some tree crops, particularly in Mediterranean landscapes, insect-mediated pollination represents the dominant mode for most fruit crops [278,303] and underpins a wide range of pollinator-dependent crops [304–306]. Consequently, orchard productivity is tightly linked to the availability and activity of pollinating insects. In many fruit production systems, managed honeybees (*Apis mellifera*) are used to supplement natural pollination, especially under conditions of reduced pollinator diversity [307,308]. High-quality colonies can improve pollination efficiency, enhancing fruit set, seed number, and fruit quality in crops such as apple and pear, thereby improving growers' economic profitability [309]. However, effective pollination often depends on diversified pollinator communities, including bumblebees and other wild bees, whose presence is strongly influenced by orchard and landscape management [310]. In contrast, some fruit crops do not benefit from pollination. In certain citrus cultivars such as clementines and other mandarins ('Nadorcott', 'Nova') cross-pollination induces seed formation, which reduces fruit commercial value [311].

Irrigated orchards can support diverse assemblages of wild pollinators, especially when management practices promote habitat heterogeneity. These include not only bees, but also other hymenopterans (e.g., wasps and ants), as well as dipterans, lepidopterans, and coleopterans, which contribute significantly to pollen transfer and the pollination of multiple plant species [312,313]. Although non-bee insects generally deposit less pollen per visit, their high visitation frequency enables them to play a significant role in pollination [312].

Plant biodiversity in orchards creates a mosaic of ecological niches that support pollinators, while agricultural management shapes the diversity, structure and habitat quality of both managed and wild communities [314]. Climate change may disrupt the synchrony between flowering and pollinator activity, reducing pollination efficiency. In this context, irrigated orchards can provide more continuous floral resources, particularly in resource-limited landscapes, while spontaneous or sown vegetation extends floral availability and supports pollinator persistence (Figure 12a,b). Irrigation reduces water stress, promoting tree growth, flowering, and vegetation development within and between rows. It also increases water availability, as drip irrigation runoff and moist microsites can serve as important drinking sources for pollinators during dry periods when natural resources are scarce (Figure 12c) (Video S2).

(a) (b) (c)

Figure 12. Illustrative examples of the orchard's role in supporting honeybees (*Apis mellifera)* activity: (**a**) *Vicia faba* sown between rows in an organic 'Lane Late' orange orchard (Algarve, Portugal, April 2026); (**b**) close-up of (**a**), showing a honeybee landing on a *Vicia faba* flower; and (**c**) several honeybees drinking water from a drip emitter in an avocado orchard (Algarve, Portugal, May 2022).

Although still understudied, evidence suggests that bee-rich orchards can benefit adjacent natural habitats by supplying floral resources that sustain pollinator populations, complement foraging, and enhance pollination services and wild plant reproduction [315,316]. Managed bee species may, in some cases, partially compensate for native pollinator declines through movement between orchards and surrounding ecosystems [316]. These effects depend on landscape heterogeneity, where moderate conversion of natural habitats can enhance complementarity between agricultural and semi-natural areas. Spatial and temporal heterogeneity supports pollinator-rich communities, while excessive forest loss reduces diversity, especially of specialist species, highlighting the importance of balance between natural and managed habitats [317,318].

Studies also indicate that, even after the flowering period, orchards may continue to function as relevant habitats for pollinators, particularly when they maintain well-developed vegetation cover. The use of orchards by bees may vary throughout the season, with increases occurring during certain periods; this pattern is associated with the availability of alternative floral resources in the herbaceous layer [319,320]. These findings reinforce the role of orchards in supporting functional biodiversity, not only through the continuity of floral resources but also by sustaining diverse pollinator communities that are essential for the stability of these agroecosystems [321].

9. Modelling Frameworks for Quantifying Ecosystem Services

Although ecosystem services in irrigated orchards are increasingly recognized, their quantification remains challenging due to the complex interactions among hydrological, physiological, and management processes. Since the economic valuation of ecosystem services depends on robust quantification methods, physics-based and AI-driven models offer promising tools to assess, predict, and support the management of ecosystem services in orchard agroecosystems [322].

Physics-based approaches can simulate water and energy fluxes together with plant physiological responses, thereby improving the assessment of ecosystem services such as water regulation and carbon sequestration [323–325]. Other approaches, such as the InVEST (Integrated Valuation of Ecosystem Services and Tradeoffs) framework, enable the estimation of carbon sequestration, biodiversity, soil erosion (through RUSLE), and other ecosystem services [326]. The RUSLE (Revised Universal Soil Loss Equation) is a widely used empirical model for estimating soil erosion under agricultural conditions at multiple spatial scales [327]. Additional process-based models, such as STICS [328] and APSIM [329], also support the simulation of carbon dynamics and a range of ecosystem services under different management and environmental scenarios.

10. Economical Valorization

10.1. European Public Policy Instruments

Orchards, as perennial and structurally complex agroecosystems, play an important role in providing ecosystem services, which largely take the form of positive externalities not remunerated by the market. This gap between environmental value and economic compensation is socially inequitable and creates a structural disincentive for the adoption of more sustainable practices, especially when they involve additional costs, production risks, or short-term income losses.

To address this societal and market failure, public policies have been implemented worldwide to promote sustainable agricultural practices, ecosystem restoration, biodiversity preservation, and the conservation of rural landscapes [330–332]. Within the framework of the Common Agricultural Policy (CAP), the European Union has developed a set of instruments aimed at compensating for opportunity costs, income losses, and expenses associated with the implementation of environmentally beneficial practices. These payments do not constitute mere income subsidies, but rather structured incentives designed to align economic rationale with environmental objectives, following the principle of "no overcompensation," that is, compensating adequately without generating undue profit [333,334].

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10.2. The Trajectory of the CAP "Green Architecture"

The 1992 CAP reform marked a paradigm shift: from a policy focused on market regulation and price support to one that progressively incorporated environmental objectives, thereby laying the foundations for its subsequent legitimation through the provision of environmental public goods [335].

In this context, "Agri-Environmental Measures" were introduced, establishing compensatory payments for the voluntary adoption of environmentally beneficial practices, alongside cross-compliance as a regulatory instrument. Mandatory mechanisms, such as "greening," were subsequently integrated into environmental conditionalities, increasing the complexity of control systems and the need for administrative simplification [335,336].

More recently, the European Green Deal has reinforced the centrality of climate and environmental objectives in agricultural policy, including carbon neutrality, biodiversity protection, and the transition towards sustainable production systems. The 2023–2027 CAP programming has consolidated this trajectory through the introduction of "Eco-schemes" and the strengthening of environmental conditionality, shaping the current CAP "green architecture", which combines mandatory requirements with remunerated incentives for sustainable practices [334,336].

Although the CAP green architecture has progressively incorporated environmental and climate objectives, evidence regarding its effectiveness remains ambiguous. The instruments largely continue to rely on practice-based measures, compensating for additional costs and income losses without necessarily ensuring measurable ecological outcomes. Several evaluations of agri-environmental measures and greening mechanisms suggest that environmental results have frequently fallen short of expectations, particularly regarding biodiversity recovery, soil restoration, and greenhouse gas emission reductions. In many cases, the predominance of prescriptive approaches has encouraged formal compliance with predefined management practices without guaranteeing effective improvements in ecosystem service delivery [337–339].

This limitation has reinforced interest in results-based or hybrid payment models, aimed at effectively remunerating ecosystem services [336,340]. The recent introduction of eco-schemes represents an attempt to strengthen the link between public expenditure and measurable environmental outcomes. However, the practical implementation of such approaches raises important methodological and institutional challenges. Reliable indicators capable of capturing ecosystem service delivery at the farm level remain insufficiently developed, while monitoring systems often involve high transaction, verification, and technical support costs. Furthermore, environmental outcomes are influenced by climatic variability and ecological uncertainty, increasing risks for farmers participating in these schemes [341].

In this context, research, pilot projects, and action-research initiatives become essential for developing robust monitoring methodologies, harmonized indicators, and locally adapted assessment frameworks capable of supporting credible and operational result-based policies. The development of reliable, scientifically validated, and operationally applicable indicators constitutes a critical prerequisite for the effective implementation of this type of agri-environmental scheme. Such indicators must be capable of measuring ecosystem services in a verifiable and cost-effective manner while remaining sufficiently flexible to accommodate different environmental conditions and farming practices [336,340]. The territorial heterogeneity of agroecosystems, particularly evident in Mediterranean orchard systems, reinforces the need for interdisciplinary research and knowledge transfer through bottom-up approaches capable of integrating local ecological variability into policy design.

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It is also important to consider that results-based remuneration models tend to be more easily adapted to multifunctional and extensive rainfed farming systems, where structural diversity favors the expression of ecosystem services. In contrast, intensive irrigated orchards focus many of their sustainable management practices—such as organic farming, integrated production, cover crops, or mulching—primarily on mitigating negative externalities associated with production intensification. In this context, the transition towards schemes strictly dependent on ecological outcomes may generate resistance and reduce farmers' participation due to uncertainties associated with climatic variability, environmental indicators, and production risks. Therefore, hybrid models combining sustainable practices with gradual result-based components may prove more suitable for irrigated orchard systems.

10.3. Voluntary Carbon Markets

Beyond public instruments, market mechanisms have emerged to economically valorize carbon sequestration in agricultural systems. Voluntary carbon markets allow companies to offset emissions by financing projects that remove or avoid CO_2 emissions, generating tradable carbon credits.

In this context, the EU has developed a regulatory certification framework, the Carbon Removal Certification Framework, to harmonize standards and strengthen environmental integrity. In Carbon Farming (Land Use and Agriculture), also called Nature-Based Carbon, removals are linked to regenerative agricultural practices that enhance climate resilience [342].

These markets face technical and institutional challenges, including the need for robust measurement methodologies, guarantees of additionality, carbon permanence, and the prevention of double counting. Nevertheless, they represent a promising mechanism to internalize the climate value of regulating services provided by orchards, stimulating regenerative soil processes.

Taken together, agri-environmental measures, eco-schemes, and voluntary carbon markets form a hybrid system of public and private incentives with the potential to accelerate the transition to more sustainable orchards. Still, integration between CAP green architecture instruments and environmental markets remains institutionally incipient and fragmented [343]. While both share the goal of valuing ecosystem services, they operate under distinct and weakly coordinated regulatory logics, generating uncertainties regarding cumulative eligibility, legal compatibility, and verification responsibilities. The absence of a coherent framework reduces predictability for farmers and limits the potential complementarity between public financing and private payments based on environmental results [344].

10.4. Policy Territorialization and Symbolic Valorization of Orchards

An emerging dimension of green architecture lies in the territorialization of agricultural and environmental policies. The integration of instruments such as Integrated Territorial Investments (ITI), zoning plans, and local development strategies strengthens the linkage between agriculture, environment, and territorial cohesion. The application of different instruments enables the environmental valorization of some ecosystem services (Table 3).

Simultaneously, international recognition initiatives, such as the Globally Important Agricultural Heritage Systems (GIAHS) of the Food and Agriculture Organization (FAO) and agricultural landscapes classified as UNESCO World Heritage, confer symbolic and cultural value to agricultural territories. In traditional orchard regions, this symbolic valorization can generate multiplier effects, linking ecosystem services with tourism, gastronomy, and high-quality products. The creation of Bio-Districts, anchored in organic agriculture promotion, also provides a powerful tool for ecological territorial governance, potentially reconfiguring agri-food value chains, consumption patterns, and relations between agriculture and society [345].

Table 3. Environmental valorization instruments and orchard practices.

Instrument	Framework	Orchard Practices	Associated Ecosystem Services
Agri-environmental and climate measures	2nd CAP Pillar	Permanent or temporary ground cover; reduced or no tillage; protection of water lines and riparian corridors; maintenance of ecological infrastructures and landscape elements; efficient water management; organic and integrated production	Soil carbon sequestration; functional biodiversity; water regulation; cultural values
Eco-schemes	1st CAP Pillar (2023–2027)	Conservation agriculture; increased soil cover; organic matter application or composting; intra-plot functional diversification; promotion of on-farm biodiversity; low-carbon practices	Emission reduction; improved soil structure; enhanced ecological resilience
Voluntary carbon markets	Market instrument	Increased tree density and longevity; varietal conversion for higher biomass; incorporation of pruned residues; systematic application of stabilized organic compounds; monitoring of soil organic carbon	Additional and measurable CO_2 removal in biomass and soil; climate resilience

11. Summary and Conclusions

Irrigated orchards are a form of intensive agriculture and, as such, are frequently the subject of severe criticism from environmental movements and society at large due to their perceived negative environmental impacts. This has fostered an atmosphere of public distrust. Climate change, characterized by rising temperatures and increasingly irregular precipitation, has further intensified this scrutiny, portraying irrigated orchards primarily as “water sinks” that compete with other essential needs.

However, this prevailing view often overlooks the vital ecosystem services that these systems provide. In this article, we have described these services based on an extensive literature review and a profound reflection on the relationship between irrigated orchards and the environment, weighing both negative and positive impacts. Given the breadth of this review, it was not possible to explore every ecosystem service in exhaustive detail; this therefore creates clear opportunities for future, more specialized research to investigate specific services with greater depth.

The authors believe that this comprehensive overview provides a compelling case that may shift the perspective of those who approach this text with an attentive and open mind. Nothing in this work is intended to minimize or disregard the negative impacts that certain irrigated orchards may have due to inadequate cultural practices or a purely productivist mindset. Rather, we assert that such practices are neither the only way to farm nor the dominant approach in many fruit-growing regions.

While this article does not specifically address organic farming or agroforestry, this is not a devaluation of their role in the agroecological transition. Instead, our focus acknowledges that even within “conventional” systems, the adoption of integrated pest management and integrated production practices has significantly transformed fruit production systems.

This review addressed three main research questions related to the role of irrigated orchards as providers of ecosystem services:

(i) Irrigated orchards were shown to provide a wide range of ecosystem services, including provisioning, regulating, cultural, and supporting services.
(ii) The scientific literature still largely reflects a productivist perspective, often underrepresenting the multifunctional role of these systems.
(iii) Important knowledge gaps persist, particularly regarding the relationships between management practices, production intensity, and ecosystem service provision, which remain insufficiently understood and require further research.

In summary, the main conclusions of this study can be synthesized as follows:

- Irrigated orchards should be recognized as multifunctional agroecosystems capable of providing significant ecosystem services alongside food production.
- The perception of irrigated orchards as predominantly environmentally harmful systems is overly simplistic and does not reflect their full ecological and socioeconomic role.
- The interactions between management practices and ecosystem service provision are complex and context-dependent, requiring further integrative research.
- Improving the quantification and valuation of ecosystem services is essential to support more effective policy design and implementation.

In conclusion, this article does not ignore the potential environmental risks of irrigated fruit crops; rather, it opens a prejudice-free perspective on their positive contributions. This is not a closed discussion but a scientifically grounded reflection intended to open a new field of dialogue among researchers, technicians, and farmers, aiming for a more sustainable future for global fruit production.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agriculture16121336/s1, Figure S1: Wildfire perimeter at an irrigated citrus orchard that helped protect nearby houses (Castro Marim, Algarve, Portugal; August 2021); Figure S2: Shredded pruning residues in the inter-row area facilitated limited fire spread while reducing fire intensity, during the wildfire (Castro Marim, Algarve, Portugal; August 2021); Figure S3: Mediterranean landscape shaped by irrigated citrus orchards (Algarve, Portugal; May 2021); Figure S4: Abandoned citrus orchard (Algarve, Portugal; June 2021); Figure S5: Improvised watering bowl installed by farmers beneath a drip emitter to retain part of the irrigation water and make it available to wildlife in the orchard (Algarve, Portugal; October 2016); Video S1: Birdsong following a wildfire, with birds using the orchard as a refuge (Algarve, Portugal; August 2021); Video S2: Several *Apis mellifera* individuals using a drip emitter as a water source in an avocado orchard (Algarve, Portugal; April 2023).

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