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Leveraging agrobiodiversity for sustainable transition in greenhouse-based intensive agriculture across Mediterranean drylands

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ABSTRACT

Dryland regions cover more than 40% of Earth's land, support around one-third of the global population, and are continuously expanding because of Climate Change and other drivers of Global Change. To overcome the harsh conditions for agriculture development and sustain food security, dryland regions have adopted intensive agricultural practices, notably greenhouse-based groundwater-dependent horticulture. The southern coastal plains of Almería, SE Spain, the driest region of the entire European continent, exemplifies this agricultural model by hosting the second largest concentration of greenhouses in the world. Since its origin in the 1960's, greenhouse horticulture in Almería has been considered a model of success, producing millions of fresh produce, contributing to the economic prosperity and social structuring, and adapting to the growing requirements of quality and safety. However, the once-celebrated "Almería's economic miracle" is currently facing signs of socioeconomic collapse and environmental exhaustion, driven by the depletion of natural resources, especially water, sand and soil, waste management challenges, e.g., plastic and biomass, and significant threats to (agro)biodiversity. We explore here a possible transition in Almería's agricultural model towards a more sustainable paradigm based on leveraging agrobiodiversity for crop diversification. This tentative model will be supported by agroforestry systems based on perennial woody crop species, which may offer high added value, adaptability to the changing and stressful conditions driven by Global Change, and potential for ecological restoration of degraded lands. We believe Almería is positioned as an ideal "laboratory" for proposing a new agricultural model that reconcile food security and environmental sustainability.

1. Introduction

Human activities, particularly since the onset of the industrial era, are severely undermining Earth's ability to sustain life. This period of Global Change is driven by forces such as habitat loss, overexploitation of wildlife and fisheries, pollution, deforestation, invasive species and, more recently, Climate Change. Climate Change—marked by global warming, erratic rainfall, sea level rise, flooding, and more frequent extreme weather events—stands out as one of the most dramatic manifestations of Global Change. Climate Change has a particularly severe impact on agricultural ecosystems, or agroecosystems, i.e., ecosystems created and maintained by humans to produce food and, in general, any product of biological origin. Agroecosystems cover over 50% of habitable land, consume more than 70% of freshwater resources, and are responsible for roughly 25% of greenhouse gas emissions (FAO, 2012; Krug et al., 2023; Mbow et al., 2017). Climate Change significantly affects agroecosystems in numerous ways, including the reduction or shifting of fertile land and freshwater resources, the spread and

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relocation of plant pests and diseases, and the decline in vital pollinators; these changes pose serious threats to crop productivity and the sustainability of food systems (Brondizio et al., 2019).

Agroecosystems thus face the difficult challenge of feeding a growing global human population, which is expected to continue to grow steadily, albeit unevenly across the planet, until at least 2050. By then, it is expected to reach nearly 10,000 million people, which will require a doubling of food production (FAO, 2009). Despite the progress achieved between 1940 and 80s during the Green Revolution (or Third Agricultural Revolution) —characterized by the widespread adoption of high-yield crop varieties, fertilizers, pesticides, and controlled irrigation— yield growth for major crop species appears to have stagnated over the past three decades. This plateau in productivity is expected to worsen under the impacts of Climate Change (Grassini et al., 2013; Zhao et al., 2017).

At the same time, agroecosystems are based on just a few annual staple crops, most of which require a large amount of inputs and are vulnerable to Climate Change; it is estimated that of the 6–7000 plant species that make up plant agrobiodiversity, i.e., which have been cultivated or consumed as food throughout history, only 30 form the majority of the human diet today and, of those 30, rice, maize, and wheat provide nearly half of global caloric intake (FAO, 2019). This reduction of crop agrobiodiversity has resulted in the homogenization of human diets and the consequent loss of potentially valuable genetic and genomic resources. In this context, the so-called orphan crops, traditionally understudied and underutilized, together with the domestication of new crops already adapted to the local environmental conditions, are attracting increasing interest for their potential to sustain plant production and ensure food security in the current scenario of Global Change (Chapman et al., 2022; Krug et al., 2023).

Agroecosystems in dryland regions, which include hyper-arid, arid and semi-arid regions, face specific challenges, often producing low yields. Consequently, many dryland regions have opted by intensification agricultural practices, particularly greenhouse-based intensive horticulture, to maintain food production (Tong et al., 2024). However, concerns are growing about the environmental and socioeconomic sustainability of this intensive agricultural approach. In this context, we analyze Almería in southeastern Spain as a key example, highlighting issues such as the depletion of natural resources (water, sand, soil), challenges in waste management (plastic, biomass), and substantial threats to (agro)biodiversity linked to this model of agriculture.

This piece reflects on growing scientific community concern for proposing responses to rethink the greenhouse-based economic model of Almería (Castro et al., 2019; Martínez-Valderrama et al., 2024), as a representative case study of other Mediterranean dryland regions that have adopted such intensive agricultural practices. We first perform a critical assessment of the threats to the socioeconomic and environmental sustainability of the model, highlighting the additional challenges imposed by Global Change. We next propose to recover agroforestry systems by leveraging local or exotic (agro)biodiversity better adapted to local and changing environmental conditions. Finally, we describe three perennial woody species that may sustain agroforestry systems and are distinguished by their high added agronomic and economic value, provisioning of ecosystem services and adaptability to changing and stressful environments.

2. Almería, the dryest region of continental Europe, hosts the second largest concentration of greenhouse horticulture in the world

2.1. Greenhouse horticulture has expanded across dryland regions in the mediterranean basin

Dryland regions, commonly defined as regions where precipitation is substantially smaller than atmospheric water demand (as quantified by potential evapotranspiration, PET), are characterized by harsh environmental conditions that include infrequent and erratic precipitations, strong winds, and intense solar radiation during most parts of the year. Dryland regions host around one third of the human population and comprise ca. 40 % of the Earth's land surface (Fig. 1A), 28% of which is placed in the Mediterranean Basin (MedECC, 2021) (Fig. 1B). This area is increasing steadily world-wide due to Climate Change and other Global Change drivers, notably overgrazing, deforestation, and unsustainable agricultural practices. It has been estimated that 100,000 million has of productive land are lost every year through desertification (UNCCD, 2023). Agriculture in these regions is typically constrained by water scarcity, extreme heat, frequent drought episodes, bared and marginal soil, irregular topography, torrential rains and strong winds.

Greenhouse horticulture provides an essential solution for growing year-round protected fresh vegetables in dryland regions (Goddek et al., 2023), especially in the Mediterranean basin, which hosts 17 out of 65 of the largest cluster areas under greenhouse cultivation in the world (Fig. 2) (Baeza and Kacira, 2017; De Pascale and Maggio, 2005; Tong et al., 2024). Greenhouses are structures designed to cultivate plants, covered with transparent materials such as plastic or glass. The transparent cover serves to protect the soil and plants from wind, pests, and diverse environmental stresses, maintain temperature and limit water loss through evapotranspiration, which significantly increases agricultural production, extends the growing season, allows for earlier harvests and increases their number. A study looking at the sustainability of greenhouse production systems through the lens of the Sustainable Development Goals (SDGs) found that using sustainable practices and technology, greenhouse farming can minimize the use of land, energy and water needed to produce very high yields (Zhou et al., 2021). However, more detailed studies are needed to completely assess the ecological implications of greenhouse agriculture and transition towards more sustainable use of natural resources and waste management (Tong et al., 2024).

2.2. Almería, a representative model of mediterranean dryland regions that have adopted an agricultural model based on intensive horticulture under greenhouse

Almería exemplifies such Mediterranean dryland regions that have based their agricultural model on year-round intensive horticulture under greenhouse relying mostly on groundwater reservoirs (Fig. 3). Located in the southeastern Iberian Peninsula and lapped by the Mediterranean Sea, the province of Almería is the driest region of the entire European continent and receives the most intense sunshine (3000 h) and days of wind per year (Tout, 1987). The predominant climate is warm and dry Mediterranean subarid, with average temperatures ranging from 14 °C in winter to 26 °C in summer. Average relative humidity is 70%, with potential evapotranspiration ranging between 1000 and 1500 mm. Annual rainfall is less than 350 mm in virtually the entire territory, generally decreasing along the W-E and N-S axes, dropping below 150 mm in some areas, such as the E coast; rainfall is markedly seasonal, usually torrential and highly irregular (Armas et al., 2011; DGIA, 2021; Tout, 1987). Almería is characterized by a great topographic heterogeneity with a marked elevational gradient that ranges from 0 m in the coastal strip to 2612 m above sea level at the highest elevation in less than 40 km (as the crow flies). Soils are typically poor and unstructured as a consequence of intense deforestation and erosion mostly resulting from mining, forest fires, and, more recently, agricultural uses, with desertification affecting more than 75% of the province (MITECO, 2008).

Despite being one of the areas of the Iberian Peninsula with the oldest human settlements, water scarcity, rugged terrain, unpredictable precipitations, typically poor soils, and strong and frequent winds have traditionally hindered human occupation, and up to the 1950s Almería was one of the poorest and most underdeveloped regions of Spain and of Europe. The development model traditionally revolved around i) subsistence dryland agriculture, characterized by low yields, with rain-fed

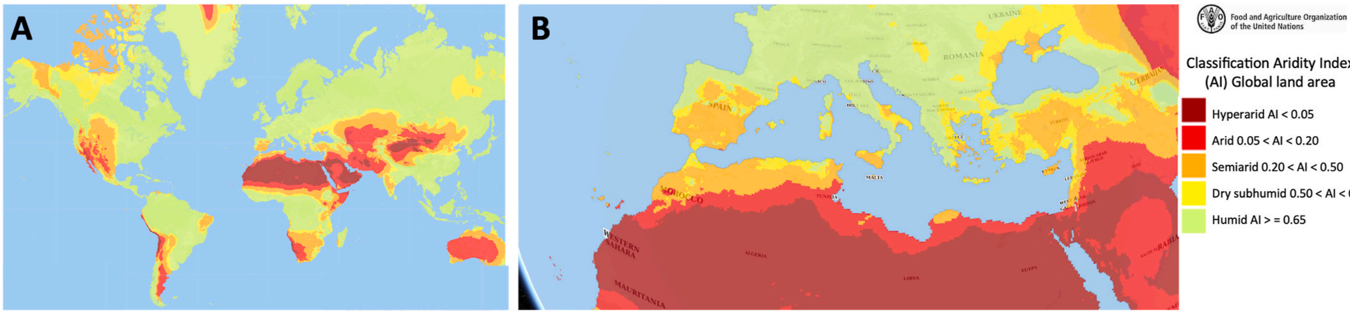

Fig. 1. Map of the global aridity index. A, Global Earth area. **B**, Zoom to Mediterranean Basin. *Source*: FAO and © Map produced by Hand-in-Hand Geospatial Platform Sun, Sep 29, 2024 19:32:15 GMT.

Fig. 2. Map of the 17 large cluster areas under greenhouse protected cultivation in the Mediterranean basin. A large cluster is defined as an area >1500 ha under greenhouse cultivation, after (Tong et al., 2024).

cereal crops, olives, table grapes or citrus fruits; ii) the use of wild crop species such as esparto grass, barilla, prickly pear, or different aromatics; and iii) mining, especially of lead and iron. Currently, the dominant economic activities are tourism, the service sector, the industry associated with the exploitation of marble and gypsum quarries, and, paradoxically enough, intensive agriculture specialized in vegetable cultivation year-round in greenhouses, which, together with all the associated industry, has become the dominant economic sector in Almería (Quintas-Soriano et al., 2016). Greenhouses extend along the coastal areas of the S of the province, mostly at the so-called 'Campo de Dalías' and other areas located W of Almería, the 'Campo de Níjar' to the E, or the surroundings of Almería, especially the 'Bajo Andarax' (Fig. 3A). Currently, the semi-arid coastal plain of Almería province hosts the highest concentration of greenhouses in the Mediterranean basin, covering 33,542 ha in 2023 (Secretaría General de Agricultura, G. y Alimentación, 2023), and ranks second globally, following Weifang, China (Tong et al., 2024). This is about 4% of the province area and represents ca. 2.8% of the global greenhouse area in the world, 16.3% % in the Mediterranean basin, half of the greenhouses in Spain and 80% of the total greenhouse acreage in Andalusia, and the acreage destined to greenhouses is continuously growing (Fig. 3B).

The origins of greenhouse-based intensive agriculture in Almería date back to June 24, 1941, with the Declaration of National Interest of the colonization of 'Campo de Dalías', and, later, to September 25, 1953, with the Decree that approved the plan for the colonization and irrigation of 'Campo de Dalías' and 'Campo de Níjar' under the auspices of the extinct National Institute of Colonization (INC), an organization dependent on the Spanish Ministry of Agriculture. At the same time, the Geological and Mining Institute of Spain (IGME) was commissioned to investigate underground water resources with the main aim of implementing modern technology for the extraction of water from aquifers; the advantages of sand-mulching ('enarenado') in plant production were also studied and polyethylene plastic, cheaper than glass, was adopted in greenhouses. Notably, much of the funding used by the INC for Spain's 1950s agricultural colonization, particularly for modernizing irrigation in Almería, came from U.S. aid linked to the McCarran Amendment (Martínez Rodríguez et al., 2019).

The first greenhouse in Almería was built in 1963 in the municipality of 'Roquetas de Mar'. The later greenhouse expansion began around 1971 with the transformation of the vineyards used for table grapes, a crop whose profitability had plummeted, into greenhouses. The typical vineyard greenhouse in Almería hardly changed its structure until the 1990s, when numerous designs and construction techniques began to emerge to improve its efficiency; the new greenhouses allowed for a higher absorption of solar radiation, and better ventilation, control of temperature, relative humidity and CO_2 (Mendoza-Fernández et al., 2021). Added to this was the application of (bio)technological innovations (integrated biological control, insect pollination), the automation and mechanization of tasks (drip irrigation, hydroponics, air conditioning, fertigation, agrochemicals), and the use of genetically

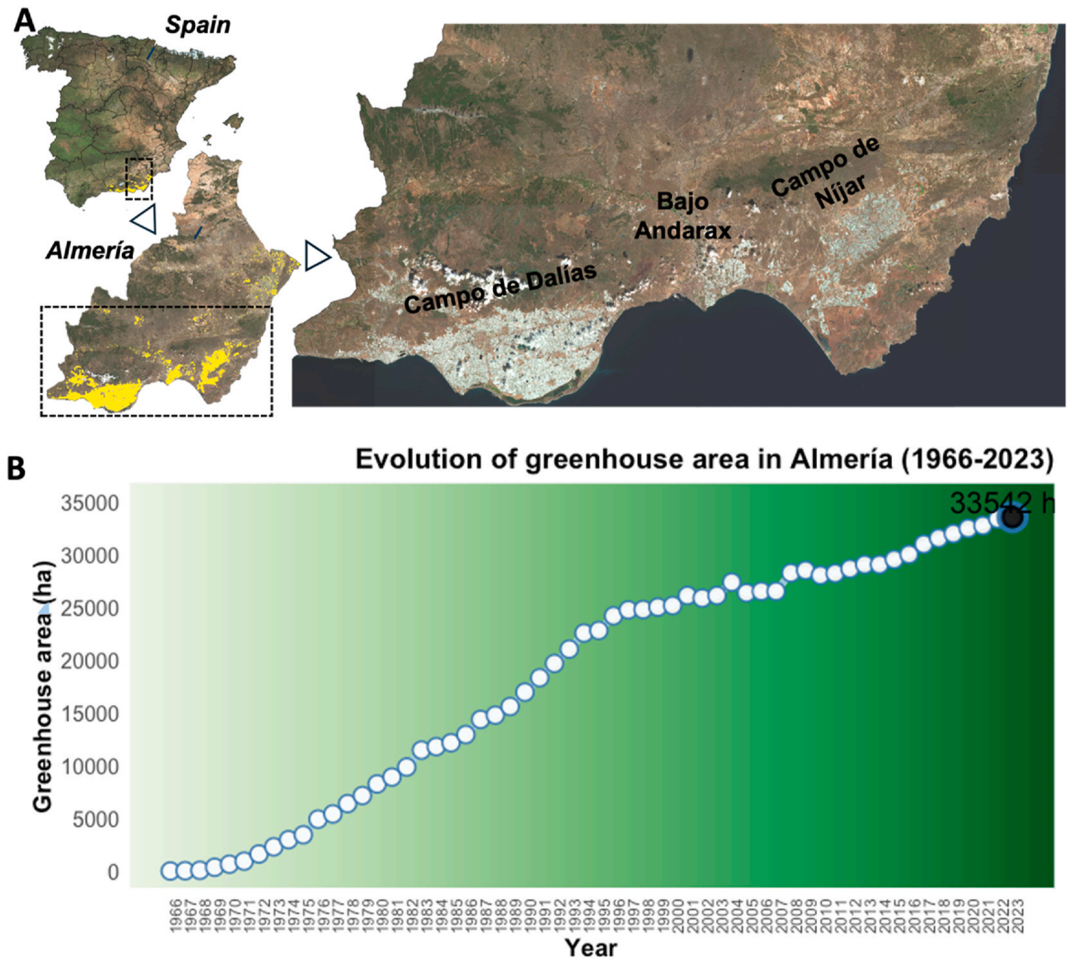

Fig. 3. Greenhouse expansion in Almería province southeastern Spain. A, the three main areas of greenhouse concentration in the southern coastal plains of Almería province ('Campo de Dalías', 'Bajo Andarax', 'Campo de Níjar') are indicated. *Source*: maps produced by data consulted from SIOSE project on Mon, Sep 30, 2024 https://www.juntadeandalucia.es/medioambiente/portal/acceso-rediam. **B**, Evolution of greenhouse area in Almería since 1966. *Source*: own elaboration based on data from (Cajamar, 2022; Secretaría General de AgriculturaG. y Alimentación, 2023).

improved crop varieties. In parallel, business forms of management and organization were implemented, as well as connection with markets, especially the Single European Market, which maintains a sustained demand for fresh out-of-season vegetable products (Quintas-Soriano et al., 2016).

3. Is the formerly deemed Almería's miracle showing signs of socioeconomic collapse?

Since its origin, greenhouse horticulture in Almería has been considered a model of success, i) producing millions of tons of fresh produce (*i.e.*, 3561 in the 2021/22 campaign, 74.9% of which is

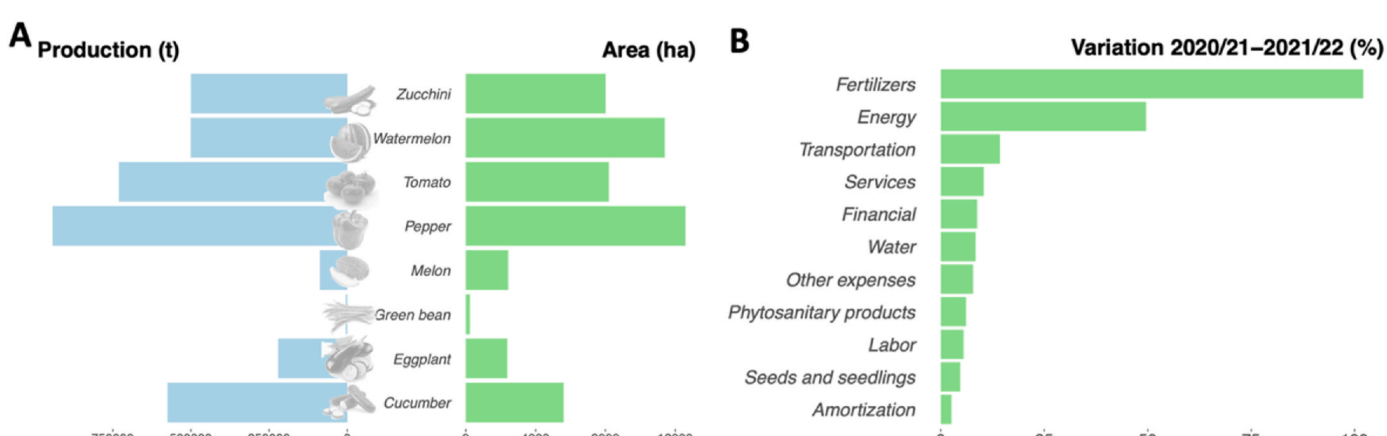

Fig. 4. The greenhouse-based agricultural model of Almería. A, Cultivated area and production of the eight main crops in the Almería greenhouses. **B**, Percentage variation in average costs per ha by spending chapter. *Source*: own elaboration based on data from (Cajamar, 2022).

exported and mostly correspond to eight main annual input-intensive and vulnerable-to-climate-change crops (Fig. 4A); ii) contributing to economic prosperity (*i.e.*, the total value of production in the 2021/22 campaign represents approximately €2940.3 million, to which must be added the auxiliary business sector, which generated a further €1311 million, and social structuring of the province, *i.e.*, most of the land is family-owned: according to some sources up to 95% of the land is in the hands of some 14,500 small family businesses, with an average of 2.3 ha of land per family; and iii) showing a potential for adaptation to the growing requirements of quality and safety of the sector, e.g., more than half of the greenhouse area in Almería has replaced pesticides by biological pest control (Cajamar, 2022). Currently, in addition to the 23, 522 family farmers dedicated to productive activity, the Almería greenhouse sector generates some 51,152 additional jobs of workers from more than 110 nationalities, mainly from Morocco and other countries in the Maghreb, sub-Saharan Africa and central Europe (Cajamar, 2022). We must also add the more than 6282 jobs related to the auxiliary industry, headed by sectors such as biotechnology, seedbeds, plant nutrition and phytosanitary products. The economic model of Almería is highly dependent on the greenhouse horticulture-based agricultural sector, representing around 13% of the Gross Domestic Product (GDP), compared to the 2.6% and 6.3% in Spain and Andalusia, respectively. Adding handling, marketing, and other auxiliary industries, this percentage raises to around 40% (Castro et al., 2019).

As a result, Almería's GDP *per capita* has gone from being the lowest in Spain in 1955 to being the highest among the Andalusian provinces from 2000 to 2009 and from 2015 to 2020 (INE, 2022). Taken together, these data have led to talk of the "Almería economic miracle" (Mota et al., 1996). However, the agricultural model of Almería is currently immersed in a crisis of profitability, low prices paid by supermarkets, which have reduced their value in Europe below production costs, and extreme vulnerability to input prices (Fig. 4B) and competitors, and it is facing serious challenges to social sustainability and equal distribution of wealth (Aznar-Sánchez et al., 2011; Carretero-Paulet, 2024; Castro et al., 2019; Delgado et al., 2016; Ibarrola-Rivas et al., 2020; Mendoza-Fernández et al., 2009, 2010, 2015, 2020).

Click or tap here to enter text.Click or tap here to enter text.For example, data from the National Institute of Statistics reveal that 'Adra', 'El Ejido', 'Níjar' and 'Vícar', municipalities in Almería where nearly 70% of agriculture under plastic is concentrated, have appeared for several years at the top of the list of municipalities with more than 20,000 inhabitants in Spain with the lowest average annual income (INE, 2022). The explanation to this arises from the fact that, although technological greenhouses require highly skilled workers, the bulk of the labor force is unskilled and seasonally hired to perform physical and routine work in harsh conditions, especially during the seasonal months; the vast majority of these are of immigrant origin, many without legal documentation and with questionable labor rights. To the ethnic segmentation of the labor market in greenhouses must be added gender segmentation, as women increasingly carry out the tasks in the handling and packing warehouses. According to data from the Spanish Ministry of Labor and Social Economy, labor and social security inspections performed between 2018 and 2022 detected more than 11,000 workers affected by various infractions of labor and Social Security regulations, mostly working without a contract or without being registered with Social Security, most of them foreigners in an irregular situation in Spain (Carretero-Paulet, 2024; Castro et al., 2019; Delgado et al., 2016). On the other hand, in the main municipalities where intensive agriculture under plastic is concentrated, there has been a proliferation of unregulated settlements where immigrant workers live in extremely precarious conditions, most of them in an irregular situation and without access to water, electricity, health, education or public transport. In 2022, the 59 illegal settlements spread throughout the province were home to a population of more than 3500 people, including a significant number of extremely vulnerable women and children (Andalucía Acoge, 2022). Other sources put this figure at between 7000 and 10,000 people.

All this taken together has led some academics to suggest the apparent imminent socioeconomic collapse of the agricultural model of Almería (Carretero-Paulet, 2024; Castro et al., 2019; Martínez-Valderrama et al., 2024). This collapse would be occurring in a context of depletion of natural resources such as water, sand for growth media or soil, difficulties in the management of waste such as plastic or biomass, and major challenges to (agro)biodiversity (Quintas-Soriano et al., 2016).

4. The challenges imposed by the agricultural model of Almería to environmental sustainability

4.1. The case of water

The arid and semi-arid regions of the Mediterranean are characterized by low and unpredictable rainfall and the absence of perennial rivers, making groundwater resources (aquifers) the main source of natural freshwater. The development of groundwater pumping and extraction technology allowed low-cost access to this seemingly inexhaustible water source and was decisive in the origin and development of the agricultural model of Almeria. Therefore, aquifers have been subject to an exponentially increasing demand, as a consequence mainly of agricultural activity, but also of the growth of urban areas and tourist activity. It is estimated that 80–85% of the freshwater for agricultural use in the province of Almería comes from aquifers, as occurs in other arid and semi-arid areas of the planet (Caparrós-Martínez et al., 2020a; García-Caparrós et al., 2017). For example, the aquifers of 'Sierra de Gádor' provide most of the irrigation water for the greenhouses at 'Campo de Dalías' (Fig. 5A), which translates into a water deficit of 65 hm^3 per year. Groundwater use is prevalent in dry southeastern Spain, resulting in the depletion of groundwater reserves up to 2014 estimated at 15 km^3 (around 400 $hm^3\ yr^{-1}$), which in turn leads to a significant decline in the piezometric level (Custodio et al., 2017). The IGME has been studying the hydrogeological functioning of this groundwater body since the 1960s, repeatedly warning about the problems resulting from their high rate of overexploitation (Domínguez Prats, 2000; González Asensio et al., 2003), which forced the Spanish government to impose limitations on the expansion of the irrigated area since as early as 1986. However, in general terms, these proposals have not been successful due to the scarce political commitment, the inefficient control mechanisms and the lack of cooperation from farmers; so much so that the irrigated area has continued to grow since then (Fig. 3B) (Castro et al., 2019). In 2016, a report from the Andalusian regional government indicated that the relationship between the recharge received by the local aquifers and the consumption of groundwater was almost 1:2 (Consejería de Medio Ambiente y Ordenación del Territorio, 2016). This relationship may become even more negative, according to the Climate Change scenarios regarding the reduction of the recharge received by the aquifers in SE Spain (Moutahir et al., 2017; Rama et al., 2022). The overexploitation of the aquifers has far exceeded their natural regeneration capacity, which has caused the demand for water by the agricultural production system of Almería to no longer be sustainable.

Likewise, for decades, the IGME has been reiterating that overexploitation is the main cause of aquifer salinization (González Asensio et al., 2003), which occurs as a result of a combination of hydrogeological processes. Salinization is responsible for significant damage and losses in horticultural crops sensitive to salinity stress and limits crop varieties to those that tolerate salinity. Furthermore, plants can only absorb a fraction of the total fertilizers applied to crops, either in the form of manures or by adding chemical fertilizers to irrigation water (fertigation); most of it is leached into the soil and can reach the aquifers. The average annual nitrate (NO^{3-}) leaching loss of greenhouses at 'Campo de Dalías' has been estimated at 175 kg ha^{-1} (Peña-Fleitas et al., 2013). Among the undesirable consequences are nitrate contamination of the aquifers and eutrophication of wetlands (Thompson et al., 2017). Indeed, the region is now classified as a Nitrate Vulnerable Zone in

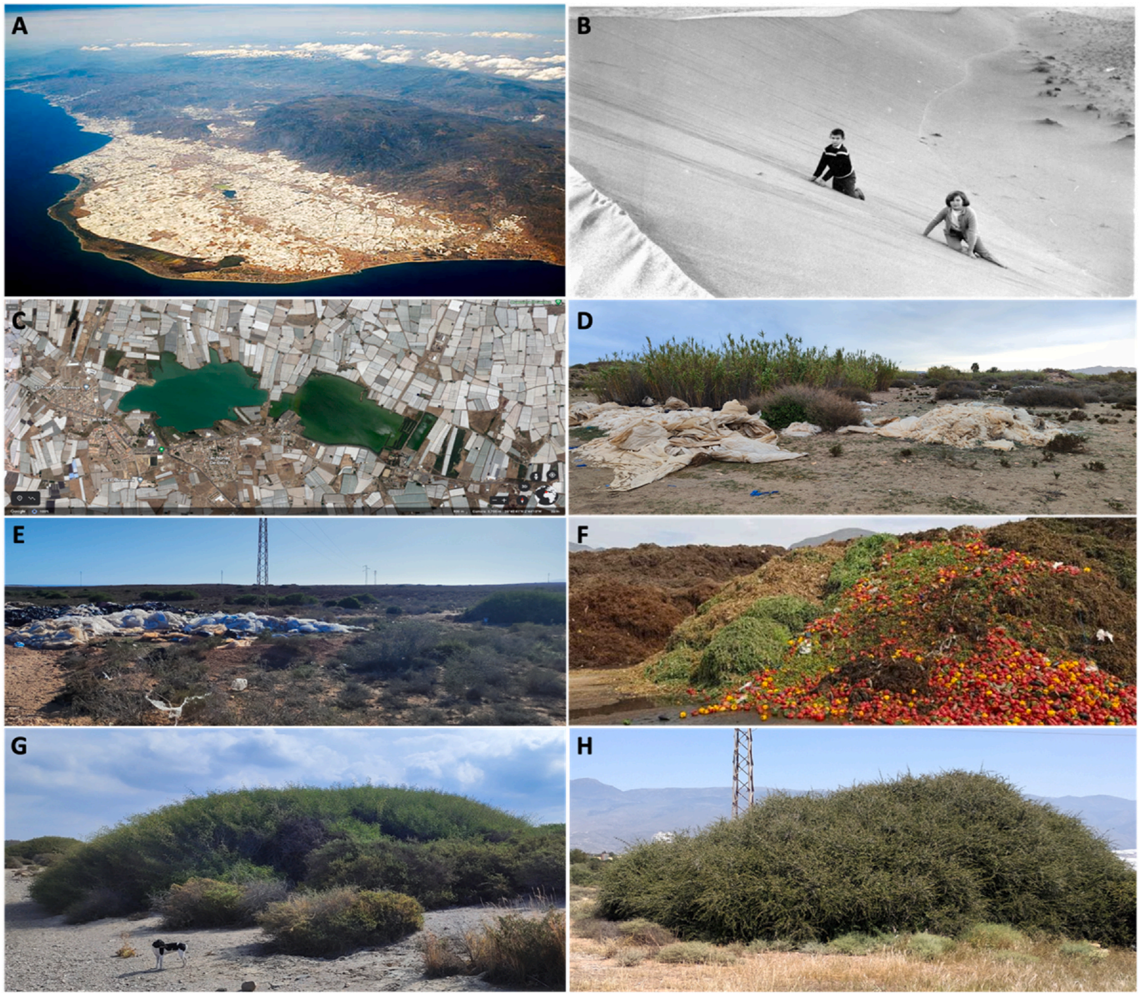

Fig. 5. The environmental impact of the greenhouse-based agricultural model of Almería. **A**, Aerial view of greenhouses at 'Campo de Dalías' and the 'Sierra de Gádor' mountain range, adapted from (Oyonarte et al., 2006). **B**, View of a dune in the 'Amoladeras' area, currently 'Cabo de Gata-Níjar' NP, in the early 1970s, adapted from (Vicente, 2015). **C**, Aerial view of the 'Balsa del Sapo', near the town of 'Las Norias de Daza (El Ejido)'. *Source*: GoogleEarth. **D**, **E**, Illegal dumping of agricultural plastic waste at the 'Cabo de Gata-Níjar' NP. *Source*: Lorenzo Carretero-Paulet. **F**, Dumping of agricultural waste biomass in Almería, adapted from (Redacción AenVerde, 2022). **G**, **H**, Two emblematic Ibero-African endemic species from Almería that are seriously threatened. *Z. lotus* and *M. senegalensis* subsp. *europaea*, respectively. *Source*: **G**, Lorenzo Carretero-Paulet; **H**, Fabián Martínez Hernández.

accordance with the EU Directive. Salinization and contamination caused by the filtration of substances such as fertilizers and phytosanitary products have led to the abandonment of 80% of the wells at 'Campo de Dalías', and to the declaration that most of the aquifers in the province do not meet the quantity and quality requirements imposed by the European Water Framework Directive (Caparrós-Martínez et al., 2020b).

Desalinated seawater and regenerated wastewater have great potential to supply agricultural freshwater. However, higher prices and energy costs combined with lower quality discourage their use by many farmers, and this in spite of i) water only representing a minor fraction of the total production costs and being strongly subsidized (Martínez-Álvarez et al., 2020), and ii) it has been estimated that adoption of alternative water resources could increase farmer's profit by up to 25% (Reca et al., 2018); in fact, most of the seawater desalination plants in Almería are either out of commission or working well below their nominal capacity and, at present, only 5–10% of the total wastewater collected is reused. On top of the high energy consumption associated to the production of desalinated or regenerated water, the impact on marine ecosystems caused by the discharge of rejected brine from desalination plants must also be considered (Panagopoulos and Haralambous, 2020). An additional negative effect of the use of desalinated seawater and regenerated wastewater results from the expected increase in total water demands, an effect common to all supply-driven strategies.

4.2. The case of sand

Greenhouse cultivation in Almería is closely linked to the sand-plot mulching technique ('enarenado'), which is used in about 85% of greenhouses (Valera et al., 2016). This technique is based on placing a substrate of silica sand several cm thick on the layer of cultivated soil and the second layer of manure or mulch. This technique improves the hygroscopic and thermal conditions of the soil, helping to retain moisture, improving fertilization, reducing the concentration of salts in the soil and creating a microclimate that favors plant growth. 'Enarenado' allows for a reduction in average water consumption per ha, for cultivating poor soils, for using irrigation water with a high percentage of salts, as well as for earlier cropping and a greater number of harvests throughout the year.

The sand was originally extracted from the province's "ramblas" (wadi) and beaches, which are free from the impurities found in the sand of "ramblas" (Viciana Martínez-Lage, 1999, 2007). This led to the appearance of marine intrusions in coastal aquifers and the origin, or intensification, of erosional processes on Almería's coastline. During the 1980s, the extraction of sand from beaches was forbidden and moved, sometimes furtively, to the coastal dune systems, which caused their degradation despite many of them being catalogued as protected natural areas (Fig. 5B) (Vicente, 2015, 2017). An example of this degradation is provided by the 'Punta Entinas-Sabinar' Natural Site, a protected area of 1971 ha, home to one of the best-preserved dune systems in Spain, and from where more than 5 million m^3 of sand were extracted. This meant the destruction of 262 ha of dunes, of which 44 were colonized by shrub associations of enormous ecological value (Viciana Martínez-Lage, 2007).

Later in the 1990s the exploitation of gravel pits began as an alternative for the supply of sand, which i) resulted in an increase in the price, ii) offered a significantly lower quality and, iii) failed to meet growing demand. The massive excavation of sediments in certain endorreic areas of 'Campo de Dalías', together with the sharp rise in the water table of the uppermost aquifer due mostly to the return of irrigation water has ended up flooding these areas, leading to the appearance of permanent artificial wetlands (Molina-Sánchez et al., 2015; Pulido-Bosch et al., 2000). The most notable example of this is the so-called 'Cañada de las Norias-Balsa del Sapo', two sheets of water located near the town of 'El Ejido', in the central area of 'Campo de Dalías', separated by a narrow strip of land (La Calle Marcos and Martínez Rodríguez, 2013) (Fig. 5C). Among the undesirable consequences of these wetlands is their use as a dumping ground for agricultural waste, as well as the risk of flooding which may involve.

4.3. Plastic waste

The construction of greenhouses depends on different plastic polymers, mainly polyethylene and polypropylene. As a result of the continued expansion of greenhouse acreage in Almería, agricultural plastic waste is growing steadily, reaching nearly 50,000 tons in 2020/21, at a rate of 1506.3 kg of plastic waste · ha $^{-1}$ · year $^{-1}$ (Castillo-Díaz et al., 2021). As a result of different environmental factors, plastics are fragmented into smaller particles; some of these accumulate in the tissues of living organisms and interact with their lipid membranes (Bochicchio et al., 2017). Microplastic accumulation in seagrass soils was found to correlate with greenhouse production areas in Almería (Dahl et al., 2021). Furthermore, certain additives that are added to plastic polymers to improve their properties, which can represent up to 50% of the final weight, decompose and release into the environment because of ultraviolet (UV) radiation from the sun. Many of these additives have been shown to cause adverse effects on different biological processes, such as neurotoxicity or alteration of hormonal systems in animals, including humans (Li et al., 2021; Oehlmann et al., 2009; Sala et al., 2019). Because of their properties, plastics are one of the major pollutants that affect both marine and terrestrial ecosystems, eventually entering the food chain (Dietz and Herth, 2011; EIA UK, 2018; Huang et al., 2020; Oliveri Conti et al., 2020).

The treatment and management system for plastic waste from Almería agriculture has an approximate cost of €0.25/kg and is heavily subsidized. However, different lines of evidence suggest that the current plastic waste processing system does not meet the growing needs of the sector, a situation that is aggravated by: i) the seasonality of its production (most of it occurs in the summer months when the production cycle ends); ii) the constant increase in the greenhouse area; and iii) certain bad disposal practices of certain farmers e.g., the dumping of agricultural plastic waste in natural protected areas (Castillo-Díaz et al., 2021) (Fig. 5D and E). It should also be noted that some agricultural plastic waste does not meet the quality criteria for recycling, so it is usually destined for burning, which leads to the production of large quantities of greenhouse gases, along with dioxins, furans, heavy metals and other toxic pollutants. In fact, it is estimated that in 2018 more than 60% of the agricultural plastic waste produced in Andalusia were not processed (Consejerías de Agricultura, 2018a; 2018b).

4.4. Agricultural waste biomass

Horticultural crops cultivated under plastic in Almería correspond to annual species that must be removed and replanted every growing season. As a result, agricultural waste biomass generated by horticulture under plastic in Almería is estimated at about 1.37 million t annually, representing on average 43.36 t ha $^{-1}$ · year $^{-1}$, with large variations depending on the crop, raising up to 84 and 147 t ha $^{-1}$ · year $^{-1}$ for tomato and pepper, the two main crops. These residues come mainly from roots, stems, and leaves resulting from pruning and from the elimination of plants at the end of the growth cycle. An additional 25% results from unsold product (Duque-Acevedo et al., 2020). Despite the EU's efforts to promote "circular horticulture" through the reduction, reuse and recycling of agricultural waste, including biomass, (EIP-AGRI Focus Group, 2017), there is currently no comprehensive greenhouse plant waste management system in the province of Almería (Duque-Acevedo et al., 2020). The absence of an integrated management system and of sufficient facilities to treat agricultural waste biomass in a circular manner represent a major logistical, environmental, and health problem (Fig. 5F).

4.5. The challenge to (agro)ecosystems and biodiversity

The uniqueness and richness of the biodiversity of the arid and semi-arid environments of the province of Almería has been documented since the 1990s, especially at the botanical level (Armas et al., 2011; Mendoza-Fernández et al., 2015; Mota, 2004; Mota et al., 1997). Indeed, the southeastern Iberian Peninsula has been included among the 25 biodiversity hotspots of the world (Myers et al., 2000). This unique diversity of species and ecosystems has led to the declaration as protected of different areas that occupy a total of 18.77% of the surface of the province (IECA), with different levels of protection, including several Sites of Community Importance of the European Natura 2000 network. The expansion of agriculture under plastic in Almería has resulted in the alteration and fragmentation of the habitats of numerous plants, some of them endemic, and animal species, especially birds and marine life (EIA UK, 2018). The result of this intense pressure on the territory is a heavily degraded environment that has been considered by the UN as an illustrative example of the deterioration of a coastal space (UN Environment Programme, 2005). Moreover, greenhouses are concentrated in the southern coastal plains of Almería, where numerous habitats of priority interest for conservation from the European Natura 2000 network unique in the continent are found. Among these are those formed by the plant communities of emblematic Ibero-African paleoendemics, examples of the sabanoid flora originating from the Lower Cretaceous period, *i.e.*, *Ziziphus lotus* (L.) Lam. and *Maytenus senegalensis* (Lam.) Exell subsp. *europaea* (Boiss.) Güemes & M.B. Crespo, as well as *Periploca laevigata* s.l. Aiton (Mendoza-Fernández et al., 2009, 2015, 2020; Mota et al., 1996), which are experiencing severe decline. Threats to the rich local biodiversity are aggravated by the construction of illegal greenhouses even in protected areas. In March 2022, the European Commission urged the Andalusian Government to stop the declassification of 75 of the 264 has that make up the 'Artos de El Ejido' SCI, protected since 2006 under the umbrella of the Habitats Directive. Despite this, the intensive use of this territory has confined it, the surrounding area has continued to be cleared for the construction of greenhouses, and even it is regularly used as a waste dump and illegal landfill (EFE, 2022; Martín-Arroyo, 2022). The construction of illegal greenhouses has also affected the 'Cabo de Gata-Níjar' Natural Park (NP) since its creation in 1987 (Mateo, 2007; TelePrensa, 2003); some of them ended up being legalized in 2008 (Plaza Casares, 2020).

5. Leveraging agrobiodiversity for crop diversification in dryland regions

5.1. Crop diversification through the (re)introduction of neglected orphan crops and the domestication of new ones

Most staple crops are input intensive and show limited tolerance to a changing climate, including the main crop species cultivated in Almería's greenhouses. Furthermore, domestication, usually focusing on yield-related traits, has resulted in a suite of undesirable changes, including the loss of genomic diversity, the accumulation of deleterious mutations, as well as altered metabolic profiles and reduced nutritional content (Gaut et al., 2018; Meyer et al., 2012). So-called orphan crop species and varieties, traditionally understudied and underutilized, are attracting increasing interest for their potential to sustain plant production and ensure food security in the current scenario of Global Change (Chapman et al., 2022; Krug et al., 2023). Andalusia in southern Spain is recognized as one of the regions in Europe with the highest levels of agrobiodiversity. Species and varieties that can be considered orphan and/or forgotten in Andalusia, but with great nutritional, agronomic and adaptive potential to local and changing environmental conditions, include various vegetables, numerous cucurbits, leguminous plants such as carobs or beans of the genus *Lathyrus*, *Phaseolus*, *Vicia* or *Vigna*, some of which have been cultivated since ancient times; buckwheat, which is an important source of carbohydrates suitable for coeliacs; and some cereals, including millet, wheat, and knotgrass (Esquinas Alcázar, 2012; Hernández Bermejo, 2013). To this list we can add a vast array of culinary herbs, as well as species once abundantly cultivated for their medicinal properties, such as hemp or capers, or different species of fruit trees, some of which have now almost disappeared from the Iberian Peninsula, or are in severe decline, such as almonds, pomegranates, figs, pistachios, carob, mountain ashes, quince, hackberry or jujubes. Key orphan species that have been part of the landscape of Spanish drylands for centuries also include certain cacti such as prickly pears. Other emerging or exotic orphan crops not previously cultivated in Spain, but in which Spain is positioning as the leading producer in Europe, include pitaya, moringa, opium poppy, and camelina, among others.

A new era of domestication of orphan and wild species has also put forward (Krug et al., 2023), ideally focusing on traits beyond yield and stress resilience, such as the restoration of degraded land and threatened ecosystems or the provision of ecosystem services. Wild species face similar challenges as many orphan crops regarding the lack of genomic resources for plant breeding, so additional research must be performed on wild relatives of major crops leveraging local biodiversity.

5.2. The potential of (agro)biodiversity to mitigate the impact of Climate Change on Almería's agricultural model

We propose here a new, alternative and/or complementary agricultural model for Almería based on a selection of orphan crops or wild relatives with strong potential to mitigate or to adapt to the effects of Climate Change. Under this premise, the species should thus be selected on the basis of their tolerance to drought, heat, climate variability, and weather extremes, allowing to address water scarcity and global warming, ultimately helping to stabilize food production while reducing groundwater overexploitation. Additionally, the species selected should stand out for their high nutritional content, multiple uses, or pharmacological properties, ultimately resulting in the broadening of the palette of crop diversity, with its consequent positive impact on (agro)biodiversity, diet quality and nutrient adequacy, as well as in the conservation of plant genetic and genomic resources. Perennial crops have the advantage with respect to annual ones of providing an array of ecosystems services that have the potential to positively impact agroecosystems (Crews et al., 2018). For example, perennial species grow deep roots over multiple years, which reduces the need of non-perennial crops to manage waste biomass every growth cycle, while protecting the soil from erosion. Furthermore, their cultivation can be performed in open fields, not only diminishing plastic and sand use, but also reducing habitat fragmentation in the region by creating green corridors for biodiversity around greenhouses.

Woody perennial crops used in ecological restoration of degraded lands as well as in agroforestry must be preferred (FAO, 2017). Agroforestry practices, i.e., the spatial and/or temporal combination of woody perennial trees or shrubs with arable crops, pastures and/or livestock in agricultural or abandoned lands, have been shown to provide an array of soil ecosystem services, including i) food and biomass production; ii) improved hydrological processes, such as infiltration in basins, thereby reducing the impact of climate variation in terms of controlling floods, soil erosion, landslides, and droughts; iii) creation of barriers against desertification; iv) Climate Change mitigation through soil carbon sequestration; v) improvement of soil properties (fertility and nutrient cycling); and vi) combat soil pollution, which negatively impacts beneficial soil microbe communities (Torralba et al., 2016; Zhu et al., 2020). Different agroforestry systems have been identified and assessed in terms of carbon sequestration potential in specific agricultural biogeographic regions of Europe subject to multiple environmental pressures (Kay et al., 2019). Among the agroforestry systems identified in Mediterranean hills pastures, there is the well-known 'dehesa', formed by a combination of cork oak, meadows and grazing. Greenhouses in Almería are concentrated in the southern coastal plains of Almería, corresponding to Mediterranean lowlands and hills arable biogeographic regions, for which a combination of holm oak and cereals or of olive trees and wild asparagus, respectively, were proposed. Drought-resistant crop tree species alternative to oaks that can be traditionally found in Almería's (silvopastoral) agroforestry systems include fig, almond, pistachio, pomegranate, and/or carob tree crops, either in association with livestock (goats and sheeps) grazing on native forage shrub and grass species, or with cereals and other rain-feed crops, e.g., grapes, esparto grass or capers (Robles, 2009; Robles and Passera, 1995; Saiz and Alados, 2012). Additional agroforestry systems that can also be found in Almería are based on native woody wild species such as *M. senegalensis*, *Z. lotus* or *Retama sphaerocarpa* L. instead of on drought-resistant crop trees, with livestock also playing a key role; here the diversity of woody and herbaceous species confirms the singularity of these habitats (Mota et al., 1996).

5.3. The examples of carob, moringa and jujube

Carob (*Ceratonia siliqua*) has been cultivated since Phoenician times in Mediterranean drylands (Fig. 6A-D). The world production of carob is about 240,000 t year $^{-1}$, and Spain, with almost 25%, is the main producer, although its cultivation has declined significantly in recent years (Tous Martí and Franquet Bernis, 2024). Carob has experienced a growing demand during the last decade, especially from the food industry. Carob trees are known for their high photosynthetic efficiency and capacity to absorb CO_2 from the atmosphere, estimated at between 50,67–188 kg · tree^{-1}, supporting the potential of carob-based agroforestry systems to mitigate the effects of Climate Change (Palacios-Rodríguez et al., 2022; Pérez-Pastor et al., 2020; Tous et al., 2013). Indeed, due to its extreme robustness, resistance to disease, heat, and water stress, together with its deep root system, carob is being used in ecological restoration and reforestation of degraded and desertified lands in areas subject to erosion and drought (Correia and Pestana, 2018; Domínguez et al., 2010).

Although it can be considered as exotic in the Mediterranean, moringa (*Moringa oleifera*) is another orphan tree crop with great potential for mitigating the impacts of Climate Change in dryland regions deforested by agricultural practices, while providing important benefits (Fig. 6E-H). Moringa is endowed with high morphological and biochemical plasticity, which allows the crop to adapt to very different local environments and tolerate stressful conditions, especially drought,

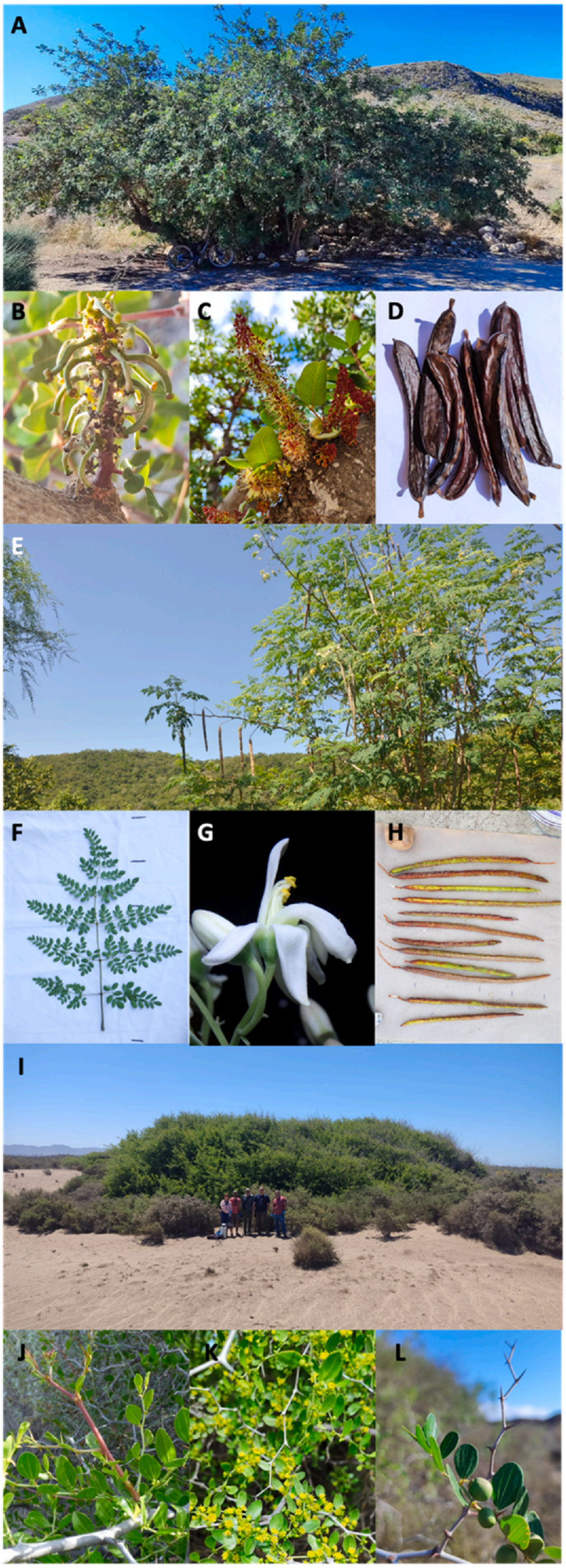

Fig. 6. Carob, moringa and wild jujube. A, **B**, **C**, **D**, tree, female flower, male flower and fruits, respectively, from carob. *Source*: Lorenzo Carretero-Paulet. **E**, **F**, **G**, **H**, tree, leaf, flower and fruits, respectively, from moringa. *Source*: Mark E Olson. **I**, **J**, **K**, **L**, shrub, long shoots, flowers and fruits, respectively, from wild jujube. *Source*: Lorenzo Carretero-Paulet and María Jacoba Salinas.

heat, and UV radiation, factors that are expected to worsen with Climate Change (Araujo et al., 2016; Boumenjel et al., 2021; Brunetti et al., 2018, 2020). Another highly desirable characteristic is its extremely rapid growth and biomass production (Oluwaseunfunmi Samuel et al., 2022; Trigo et al., 2020). Originally native to India, its cultivation has spread to different tropical and subtropical areas of the planet characterized by nutrient-poor soils, water scarcity, and high average annual temperatures, including the Mediterranean Basin (Trigo et al., 2020; Vaknin and Mishal, 2017). A report published in 2016 listed several successful agricultural trials carried out in different locations in the SE of the Iberian Peninsula (Godino García, 2016), including Almería.

Third, Z. *lotus*, though not cultivated as a crop, their fruits are considered an excellent source of many nutrients and are consumed fresh, dried, and processed by local populations (Fig. 6I-L); the plant is also used in traditional medicine and cosmetics (Abdoul-Azize, 2016; Dahlia et al., 2023). *Z. lotus* forms arborescent shrubland ecosystems considered as critically endangered in Europe, with the best conserved populations found in the 'Cabo de Gata-Níjar' NP in Almería, SE of Spain, protected under the Priority Habitat 5520 of the Natura 2000 network (EU Directive 92/43/EEC). This drought-resistant, deep--rooted, long-lived, winter-deciduous, thorny, intricate shrub forms massive canopies on top of dune-like accumulations of sand and organic material. These fertility islands facilitate the success of communities formed by specific plants and animal species, thus becoming the key engineers in these semiarid ecosystems (Constantinou et al., 2021). Indeed, *Z. lotus* has been shown to contribute to increased primary productivity in arid areas through hydraulic lifting processes that increase soil moisture and organic matter content, facilitate nutrient uptake and influence soil aggregation. These positive effects on soil processes may favor neighboring plant survival, establishment, growth, and reproductive success, a type of interaction known as facilitation. Facilitation has been applied to ecological restoration in different degraded environments, including semiarid abandoned fields in Almería (Padilla and Pugnaire, 2006, 2009). Additional ecosystem services provided by *Z. lotus* include its role as a carbon reservoir, in erosion control, and as a habitat for beneficial arthropod fauna useful in biological pest control (Constantinou et al., 2023; Giagnocavo et al., 2022; Tirado, 2009; Torres-García et al., 2022). In addition, the genus *Ziziphus* is formed by around 100 species, including the long-lived, resistant to poor soils, drought and heat/cold, as well as economically important *Z. jujuba* (Chinese jujube), one of the oldest cultivated fruit trees in the world (Liu et al., 2014). In Spain, it has been cultivated for centuries, mostly in the southeastern region, as an ornamental plant or marginal crop and is commonly found feral; therefore, *Z. jujuba* can be considered an orphan crop species in Spain (Melgarejo Moreno and Salazar Hernández, 2003). At this respect, in-depth studies of *Z. lotus* will assist in i) the identification of varieties of *Z. jujuba* best adapted to local and changing environmental conditions; and ii) unraveling the genomic basis of (water) stress-related and other desirable agronomically traits.

6. Conclusions

Greenhouse horticulture relying on groundwater reservoirs provides an essential solution for growing year-round fresh vegetables in dryland regions. Consequently, greenhouse-based agriculture has expanded globally, and especially across the Mediterranean basin, with Almería, SE Spain, representing the largest concentration. However, after decades of initial success, concerns are raising about the socioeconomic and environmental sustainability of this intensive agricultural approach. We propose here leveraging agrobiodiversity for crop diversification to help transition to a more sustainable agricultural model for Almería. This tentative model will be supported by agroforestry systems based on perennial woody species distinguished by their high added agronomic and economic value, provisioning of ecosystem services and adaptability to the changing and stressful environments characteristic of Global Change. Although the conclusions from this study can be extrapolated to other dryland regions with greenhouse-intensive agriculture, Almería stands out as an ideal "laboratory" for testing this model due to its distinctive ecological, geographic, and climatic conditions, its rich local (agro)biodiversity, the evolution of its agricultural practices, and its demonstrated adaptability over 60 years. We believe this agricultural model is best suited to guarantee food security for a growing human population under Global Change in an environmentally and socioeconomically sustainable manner and contributes to achieve UN's SDGs 2 ('Zero Hunger'), 6 ('Clean water and sanitation'), 12 ('Ensure sustainable consumption and production patterns'), 13 ('Climate action'), and 15 ('Life on land) by 2030.

CRediT authorship contribution statement

Lorenzo Carretero-Paulet: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Investigation, Formal analysis, Conceptualization. **Antonio J. Mendoza-Fernández:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis. **Francisco Javier Alcalá:** Writing – review & editing, Visualization, Validation, Investigation. **Antonio J. Castro:** Writing – review & editing, Visualization, Validation, Investigation, Formal analysis.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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