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Uberizing Agriculture in Drylands: A Few Enriched, Everyone Endangered

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Abstract
The future of water resources relies heavily on food production. Large-scale agriculture, driven by irrigation technology and cost reduction, has transformed traditional dryland croplands into a very profitable but environmentally and socially impactful agribusiness. The study of groundwater-dependent food systems is fragmented. Hydrology, on one hand, concentrates on water resources while overlooking surface agricultural processes. Meanwhile, the agro-economic sector is fixated on optimizing resource utilization for short-term profit maximization. Consequently, numerous adverse environmental and social consequences are overlooked by these conventional approaches. To steer resource usage and our food systems in a new direction, prioritizing the integration of this collective knowledge is imperative. Here, we analyze the impacts of greenhouse agriculture in SE Spain, one of the global hotspots of fruit and vegetable production. Through the lens of the treadmill of production theory we uncover the model's significant profitability and its environmental and social effects, which include unequal wealth distribution, precarious working conditions, and the depletion and pollution of belowground water reserves. Reducing water use and limiting the development of new irrigated areas, using crop species adapted to available water resources, and empowering farmers against large distributors are key measures to avoid the social and economic collapse of this region, and of other dryland areas that have followed a similar unsustainable development model. The need for these changes becomes more pressing as the impacts of climate change continue to escalate. Within this context, groundwater reserves represent vital strategic resources that must not be wasted.

Keywords Drylands · Desertification · Treadmill of production · Groundwater degradation · Agrobusiness · Water demand management

1 Introduction

There is a heightened awareness of the importance of consuming healthy foods, leading to a surge in demand for plant-based diets (Willett et al. 2019) that are also organic and free of pesticides (Rana and Paul 2020; Le-Anh and Nguyen-To 2020). In addition, consumers are increasingly concerned about the environmental and social impact of food production

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(Janssen and Hamm 2012; Grunert et al. 2014). Despite this, it is projected that by 2030 there will be more obese (1469 million) (Lobstein et al. 2022) than undernourished (842 million) (von Braun et al. 2023) people globally. Moreover, the current food production system has major environmental impacts, including the generation of plastic waste, soil erosion, CO_2 emissions, eutrophication, biodiversity loss, and groundwater degradation (UNCCD 2022; Ritchie and Roser 2023; von Braun et al. 2023). To compound these problems, one third of all food produced is never consumed (FAO 2011). The main issue at hand is the intensification of the agricultural model, which has led to a significant and expanding water gap (FAO 2021; Martínez-Valderrama et al. 2023b). Addressing this scarcity solely through the supply side has proven to have a rebound effect, widening this gap, as shows widespread decline in groundwater reserves (Bierkens and Wada 2019; Scanlon et al. 2023) and lakes (Yao et al. 2023). Therefore, it is crucial to examine the underlying causes of these agribusiness practices (which are becoming more focused on profit rather than agriculture) to curb the widening disconnect between water usage and availability. Climate change exacerbates this problem further, making the need for action even more urgent.

Agricultural systems linked to the use of groundwater are of particular significance. Institutions such as the World Bank (Rodella et al. 2023) and UNESCO (UN-Water 2022) have highlighted the strategic role of these water reserves in relation to food systems. Thus, for example, the last Food Day (FAO 2023) was dedicated to water resources, highlighting their close relationship with food systems. Here we analyze the case of Almería (SE Spain), which has moved from being a poor and marginalized area in the 60s to one of the largest global producers of fruits and vegetables (Juntti and Downward 2017) thanks to the development of greenhouse agriculture and the exploitation of groundwater reserves.

The aim is to integrate the various aspects of a groundwater-dependent food system. It is a very complex socio-ecosystem that has traditionally been approached in a partial way, hence its unsustainable dynamics and the multitude of associated problems. Indeed, as Postel (1999) put it, it is a business with sand pillars. Despite the recurrent calls for multidisciplinarity under various paradigms that attempt to provide an integrated vision of nature and human beings (socio-ecological systems (Berkes and Folke 1998), ecological economics (Costanza 1996), the water-food-energy nexus (Ringler et al. 2013), or the notorious Agenda 2030 and its the Sustainable Development Goals in the context of food systems (Herrero et al. 2020)), the truth is that partial visions are still offered in many cases.

Thus, from the field of hydrogeology, groundwater has been studied in great detail, but leaving aside the dynamics of the main extractive activity, irrigated agriculture, which destabilises the system. From an agronomic point of view, much attention has been paid to efficient water use, which, far from improving groundwater conditions, has worsened them. As described by the Jevons' paradox (Jevons 1866), in many irrigation systems a rebound effect (Grafton et al. 2018) occurs where increased efficiency leads to increased water consumption; i.e. water is used so efficiently in the production system that there is nothing left for other ecosystem functions.

Despite the area's poor water balance and huge consumption, water is taken for granted. Political speeches about the infinity of water, the betting on new technologies as a silver bullet to solve the water shortage at a stroke and forever, such as the construction of desalination plants, or the fact that the word water is hardly mentioned in the reports on the profitability (Fundación Cajamar 2023a) of this agribusiness (barely 5 times in more than 70 pages; one of them in the profit and loss account to say that water accounts for 2.5-3% of costs), give an idea of the disconnection between the production system and the natural resource on which it is based.

There is a very different view from researchers in the field of environmental sciences, who describe in various papers and reports the ecological damage caused by this form of production (depletion of aquifers, marine intrusion, pollution by plastics, erosion, loss of biodiversity, etc.). Finally, the social effects of these food systems go unnoticed by a large part of the public (including academics), as there is no mention of the distribution of wealth or the poor working conditions of many workers, generally immigrants.

The value of this work is to bring together all this scattered information to give a complete picture of how, why and what are the consequences of groundwater use in the drylands in such an intensive use as greenhouse agriculture. For this purpose, we use the Treadmill of production economic theory (Schnaiberg 1980), which is driven by large-scale economic principles that prioritize cost reduction in production but overlook negative externalities associated with the process. By doing so we aim to examine the underlying mechanisms of current agribusiness in drylands, which is based on the exploitation of favorable climatic conditions and the exploitation of groundwater, fueled by large investments seeking high economic returns.

Only by understanding the various interactions between the different actors involved and the different impacts, positive and negative, economically, socially and environmentally, and including a social science perspective on problems related to water resources degradation (Martin-Ortega 2023), is it possible to design solutions that can be truly sustainable (i.e., economically, socially and environmentally). The urgency of implementing appropriate measures becomes even more relevant in a context of climate change which, on the one hand, decreases the recharge of aquifers (REF) and, on the other hand, increases the demand for groundwater resources (El-Nashar and Elyamany 2023; Martínez-Valderrama et al. 2023b). In light of the uncertainties posed by climate change, it is imperative to regard groundwater reserves as critical strategic assets that require prudent management and should not be wasted in the short run (Maliva 2021; Scanlon et al. 2023).

2 Economic Miracles with Adverse Outcomes

2.1 A Garden in the Desert

Almería, located in the SE corner of Spain (Fig. 1A), is the most arid zone in continental Europe and is dominated by the desert-like aspect of its landscape (Fig. 1B). Precipitation fluctuates from less than 200 mm yr^{-1} in the coast to 400 – 500 mm on the mountain tops. High temperatures and intense sunshine (3000 h yr^{-1}; Tout 1990) cause a high evapotranspiration rate. The main water reserves of Almería are underground, with an estimated reserve of around 70,000 hm^3 (IGME and Junta de Andalucía 1998). In the middle of the last century, Almería was synonymous with poverty and backwardness. The experiments carried out by the "Instituto Nacional de Colonización" (Spanish Ministry of Agriculture) in the 1960s made it possible to combine a cultivation technique little known in the area, *enarenado* (sanding-plot), with the climatic conditions and abundant groundwater (Tout 1990) of the region to start its agricultural development. A wide variety of horticultural crops began to be grown in the area that, protected from the wind by plastic-covered greenhouses, gave extraordinary yields (Caparrós-Martínez et al. 2020). Spain's entry into the European Union gave access to a market eager for fruit and vegetables, generating unprecedented wealth in the province, to the point that its economic development became known as the "Almerian Miracle" (Juntti and Downward 2017). Technological innovations, for

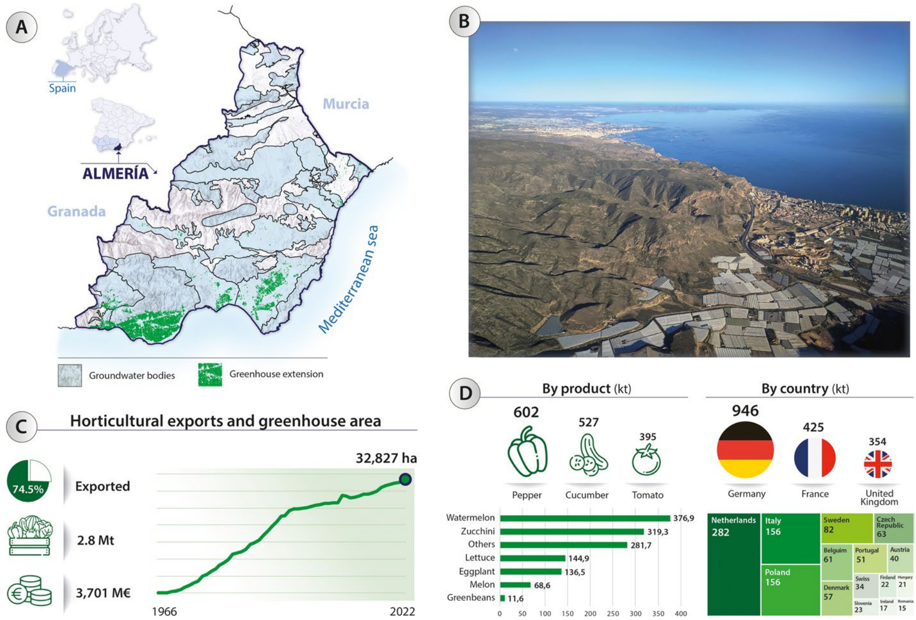

Fig. 1 **A** Location of groundwater bodies and greenhouses in Almería (Junta de Andalucía. 2016; Junta de Andalucía. 2019) **B** View of greenhouses in the area (Picture by A. Guerrero). **C** Evolution of greenhouse area (Fundación Cajamar 2023b). **D** Exports of fruit and vegetables from Almeria according to product and country of destination (Fundación Cajamar 2023b)

example, establishing efficient irrigation systems that are now used in 99.9% of the greenhouse surface area (Céspedes et al. 2009) or replacing the use of pesticides with biological pest control, and the area covered with plastic greenhouses, which now exceeds 32,800 ha (Fundación Cajamar 2023b), have not stopped since then.

The annual figures for the sector speak for themselves: 3823 kt produced, with a value of 2977 M€, and additional 1311 M€ in the auxiliary industry (Fundación Cajamar 2023b). The agricultural sector now represents 35 – 40% of the provincial GDP and it exports most of this production (2864 kt) to more than 30 countries (worth 3701 M€, Fig. 1C, D). The sector also provides employment for over 100,000 workers: 74,674 on farms, 6282 in the auxiliary industry, and 24,000 in the handling and distribution of fresh produce (Fundación Cajamar 2023b).

2.2 Groundwater Collapse

The most important impact of this intensive agricultural model is the depletion of groundwater resources. The substantial water demand of intensive irrigated agriculture poses the most immediate threat to greenhouse agriculture. Despite it was evident decades ago (IGME and Junta de Andalucía 1998), and the different legislations that have tried to tackle it, the problem has been getting steadily worse. The failure of the administration itself to comply with the legislation that warned of their exploitation (Real Decreto 2618/1986 1986) is the most tangible evidence that development is above everything else, including the very survival of the socio-economic system at the mid- to long-term. In 1996, the land-use plan for Almeria stated that "Bearing in mind that intensive agriculture is the main activity in the economic system [...] it is necessary to consider it as not dispensable…. it is more coherent and correct to approach the design of a general model for the use of resources, especially water, which allows sustainability without questioning the evolution of the sector"(Contreras 2002). More than twenty years later, the official territorial planning repeats the same message (Junta de Andalucía. 2002), but with any practical implications so far (Fig. 1C).

In the Campo de Dalías-Sierra de Gádor aquifer, the water plundering began in the sixties and was confirmed in the following decades. It went from 10 hm^3 yr^{-1} in the 70s to 45 hm^3 yr^{-1}in the 80s. The salinization of the coarse aquifers brought it down to 20-25 hm^3 yr^{-1}. This is when the search for alternative sources of water and the drilling of deeper wells began, to reach annual pumping levels of 120 hm^3 yr^{-1}. (Pulido-Bosch et al. 2020). In the case of the Campo de Níjar aquifer there is no possibility of accessing deeper water layers. The pumped fresh water has been replaced by seawater and since the 1990s the aquifer has been completely salinized. Its water is used to mix with water from desalination plants to obtain a salt concentration suitable for crops such as tomatoes, which require water with high conductivity.

According to the basin plans of the Ministry of the Environment (MITECO 2019), in the Dalías field 154 hm^3 yr^{-1} are extracted (158% of the annual recharge). In Campo de Níjar the annual pumping is 32.7 hm^3 (250% above the recharge), and in the Medio-Bajo Andarax (the aquifer located between the two previous ones), 18.9 hm^3 yr^{-1} are extracted (149% more than the recharge). Regrettably, this situation is far from unique in the southeastern region of the Iberian Peninsula (the most arid region in Spain, next to the Canary Islands. Groundwater mining is the prevailing practice in approximately 9000 out of the 13,000 km^2 encompassing the 250 aquifers in this region. The depletion of groundwater reserves up to 2014 is estimated at 15 km^3 (around 400 hm^3 yr^{-1}). As a consequence, this has resulted in a decline in the piezometric level, with depths ranging from 65 to 350 m between 1980 and 2013 (Custodio et al. 2017). A high proportion of the groundwater bodies in Almería are in a poor condition, both quantitatively and qualitatively (Fig. 2A). Freshwater depletion in coastal aquifers has led to seawater intrusion, whereas the widespread use of nitrogen fertilizers has resulted in nitrate contamination due to leaching of irrigation returns (García-Caparrós et al. 2017). Many greenhouses are located in areas declared a Nitrate Vulnerable Zone under the EU Nitrates Directive, which requires the adoption of improved management of both irrigation and nitrogen (Castro et al. 2019).

2.3 Plastic Pollution

Greenhouse agriculture uses large amounts of plastic, as it is involved in most of the components and techniques used in the production process. Agriculture accounted for 63% of all agricultural plastic waste in Andalusia in 2018, and an estimated 30,000 t yr^{-1} of greenhouse plastic waste is abandoned in the western sector of Almería alone (Junta de Andalucía. 2021a, 2021b). Although current legislation requires recycling (Junta de Andalucía. 2021a, 2021b), the discontinuation of plastic exports to China (Igini 2022) has resulted in the collapse of the plastic recycling system. The Integral Waste Plan for Andalusia (Junta de Andalucía. 2021a, 2021b), acknowledges that even though 85% of collected agricultural plastics are sent to recovery facilities, the destination of 75% of the remaining waste remains unknown. Efforts have been made to dismantle illegal plastic waste export networks (Planelles 2021),

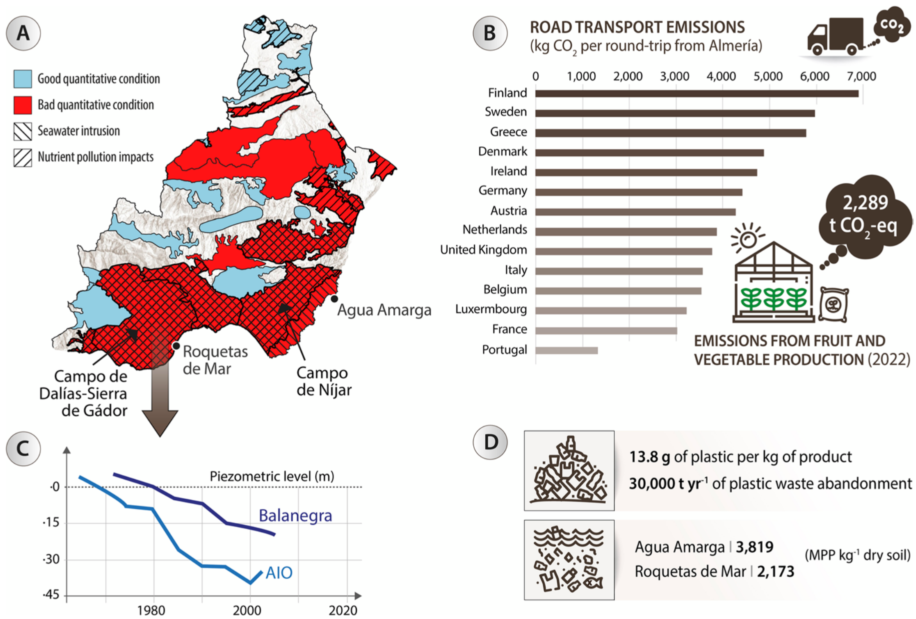

Fig. 2 **A** Status of groundwater bodies in Almería (MITECO 2019; Junta de Andalucía 2023a). **B** Agricultural greenhouse gas emissions derived from production (Clune et al. 2017; Fundación Cajamar 2023b), and transport of fruit and vegetables to European markets (Martínez-Valderrama et al. 2023a). **C** Decline in two piezometric monitoring points in the Campo de Dalías-Gádor groundwater body (Custodio et al. 2016). **D** Plastic needs (g) to produce one kg of product (Castillo-Díaz et al. 2021), plastic abandonment (Junta de Andalucía 2021b), and concentration of microplastic particles (MPP) in the seagrass soils of Roquetas de Mar and Agua Amarga (Dahl et al. 2021)

and ongoing police investigations are addressing the issue (Ministerio del Interior 2023). The reality is that there are plastics everywhere in Almería (Sánchez 2021), and worrying concentrations of microplastics have been measured in the seagrass meadows along the coast (Dahl et al. 2021) (Fig. 2D). The damage caused is not only due to the fragmentation of the material, but also to the presence of various additives in plastic materials, such as benzyl phthalate, which can cause harmful effects on the health of organisms (Castillo-Díaz et al. 2021).

2.4 Carbon Footprint

Agribusinesses heavily rely on fossil fuels. The manufacturing of plastics used in the industry directly depends on oil or its byproducts. Moreover, energy requirements have surged due to the movement of water within the system, including pumping and desalination. As groundwater has been degraded, desalination plants have been constructed, but the high energy consumption in reverse osmosis and pretreatment processes have contributed to an increase in carbon emissions. For instance, the Carboneras (literally in Spanish this means "charcoal bunker") desalination plant, the world's second largest with a capacity to produce 42 hm^3 yr^{-1} of fresh water (Martínez-Álvarez et al. 2019), currently relies on a coal-powered thermal power plant (MITECO 2023) (although efforts are underway to power it with solar energy, León 2023a). Consequently, the carbon footprint associated with irrigation is substantial, ranging from 1.30 – 1.48 kg CO_2-eq m^{-3} for desalinated water and 0.29 – 0.33 for water pumping, compared to a maximum of 0.03 for irrigation with surface water (Martínez-Alvarez et al. 2016). Carbon emissions linked to agribusiness include inputs from chemicals, fertilizers, fuel, energy for irrigation, machinery used in cultivation, harvesting, and processing, as well as transportation and refrigeration to regional distribution centers. These emissions are estimated (Martínez-Valderrama et al. 2023a) at 2289 t CO_2-eq yr^{-1}. Additionally, transportation from Almería to European markets accounts for an estimated (Martínez-Valderrama et al. 2023a) 6982 t CO_2 day^{-1} (Fig. 2B). This estimation is based on the substantial volume of transportation involved in supplying Central European markets with fruits and vegetables. Approximately 1500 to 2000 trucks are deployed daily for this purpose (Fernández 2020; Fenoy 2022). These trucks, with an average load of 16 tons (Fernández 2020), cover extensive distances exceeding 4000 km to reach various European countries (the main destination, the capital of Germany, is situated 2600 km away). To calculate the estimated emissions, we consider an emission rate of 105 gCO_2 km^{-1} t^{-1} (Kilgore 2023).

2.5 Habitat Destruction

During a period of rapid greenhouse expansion in the region, prioritizing development and wealth creation over environmental concerns has resulted in devastating impacts on the ecosystems. The widespread use of *enarenado* led to the extraction of a staggering 17.5 hm^3 of coastal dune systems and alluvial beds with significant ecological value (Viciana 1999), hindering their natural regeneration. The construction of greenhouses has eradicated unique ecosystems, such as the artal (*Maytenus senegalensis*) (Mendoza-Fernández et al. 2015) and the *Ziziphus* communities, both designated as a Priority Habitat under Directive 92/43/ECC (Castro et al. 2019). These ecosystems now occupy 115 ha, a mere 5% of their size 70 years ago (Martín-Arroyo 2022).

3 The Root of the Problem: Large-Scale Production to Be Competitive

3.1 Agribusiness in SE Spain

The socio-ecosystem studied, which consists of groundwater-dependent greenhouses, aligns well with the Treadmill of production theory (Sanderson and Hughes 2019). According to this theory, there is a shift towards accumulating capital to replace labor with new technologies aiming to increase profits. This change is driven by the goal of enhancing output, similar to the Green Revolution that occurred in the mid-twentieth century (Sumberg et al. 2012). The study region provides a clear understanding of the key mechanisms driving the Treadmill of production. Firstly, agriculture directly extracts natural resources (in this case, groundwater), making it closely linked to the ecosystem in the production process. Secondly, agriculture exemplifies how capital motivates the self-exploitation of labor, creating a growing dependency on production and accumulation as the treadmill progresses.

Figure 3 illustrates how the spiral works in which farmers are trapped in a process, where sustained technological advances create productivity gains for the benefit of progressive farmers (it is important to note the competitive advantages of early adopters, whose success attracts other farmers), but where the result is also increased supply, falling prices and thus the need for new achievements in technology. Thus, if farmers want to remain in the business, they need to implement new technology, and

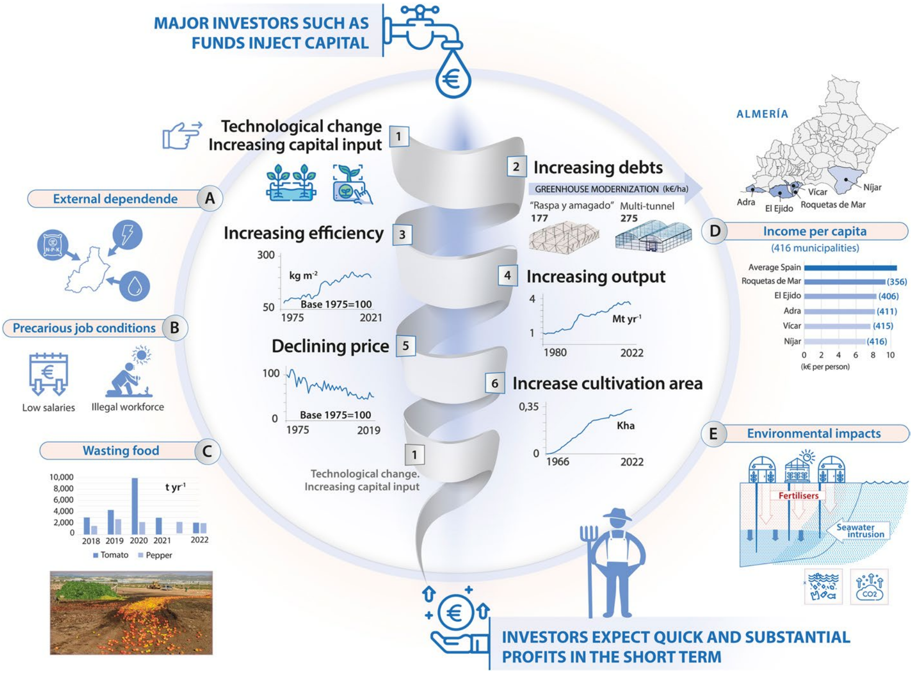

Fig. 3 The Treadmill of production in action, exemplified by greenhouse agriculture in Almería. Investments enable the activation of this mechanism, which is described by six steps (1. Increasing capital input; 2. Increasing debts; 3. Increasing yields/efficiency; 4. Increasing output; 5. Declining product prices; 6. Increasing cultivation area) that repeat themselves. These investments seek high short-term profitability but, in addition to impoverishing smallholders, have a range of negative externalities, including: **A**) Creating a system dependent on external inputs; **B**) Precarious labor; **C**) Food waste due to oversupply (Martínez-Valderrama et al. 2020a); **D**) Poor wealth distribution (INE 2021); **E**) Severe environmental damage

the market conditions make it difficult and almost impossible to escape the treadmill (Hansen and Hansen 2019). Investment in irrigation technology is an important part of the agricultural treadmill, as well as creation of increasingly sophisticated structures or investments in biotechnology (smart agriculture) and water (desalination, recycling, etc.) (Step 1 in Fig. 3). This substitution of labour for capital results in a series of investments that generate debt (Step 2). For example, the cost of 1 ha of greenhouse ranges 177,000 – 275,000 € (Junta de Andalucía 2015), and input costs (seeds and seedlings, fertilizers, phytosanitary products, energy) add up to around 20,000 € ha^{-1} (Fundación Cajamar 2023b) (Step 2). To amortize the fixed and operating costs of the new technology, production generally had to be substantially increased. As farmers extend irrigation infrastructures across more land, production can be expanded, potentially raising income. The more extensive use of capital-intensive irrigation also allows water to be used more productively, or efficiently, in market terms (Step 3). Farmers that use water more productively should generate higher incomes because they are producing more "crop per drop". In fact, this is a claim that is used to justify the allocation of resources there, where water generates more wealth than anywhere else (Martínez-Valderrama et al. 2020a). The treadmill is exacerbated by overproduction (Step 4). As competitors adopt all the technical improvements available on the market, production levels increase, supply can exceed demand, and prices decline (Step 5). When prices fall, and once indebted and with all the investment made, it is normal to continue investing to increase the volume of production to compensate for the fall in prices. Thus, the system is turned upside down, increasing the cultivation area (Step 6) and investing again in more efficient production systems, in terms of production per unit area (Step 1). As a result, the area of greenhouses and what is produced per m^2 increases, which implies a higher consumption of resources. This conceptual framework captures a familiar dynamic for many farmers: some appear to "get ahead" one year while, in reality, they remain in the same position the following year, with a stagnant or even declining standard of living due to the depletion of a non-renewable resource, i.e., is the image of a society that is running without moving forward (Sanderson and Hughes 2019).

The treadmill depicted in Fig. 3 represents a centrifugal force driven by significant capital investments aiming for high short-term returns. However, this approach pushes small producers out of business as they are unable to sustain such rapid investment or debt. This model of production results in models of fleeting wealth, where investors withdraw their capital once the region's advantages diminish. In the aftermath of the 2008 financial crisis, the agri-food sector has emerged as a safe haven (Clapp 2019), prompting investors to seek higher returns in lucrative ventures. As a result, there is a growing trend of investors from Almeria shifting their focus towards Morocco (León 2023b), where environmental regulations are relatively more relaxed, and labor costs are lower.

Moreover, these investments do not usually stay in the territory as they only use it for their own benefit. Many of the municipalities with a strong vocation for greenhouse agriculture are among the poorest in Spain according to official statistics (INE 2021). For example, Níjar, which in the 1960s was one of the less developed municipalities in Spain, finds itself, 60 years later and after degrading its groundwater, having the lowest per capita income of the 416 Spanish cities with more than 20,000 inhabitants (7097.2 € $person^{-1}$) (Fig. 3D). Although we cannot deny that in absolute terms Níjar is much better off than it was 60 years ago, in relative terms nothing has changed.

Despite these challenges, there is immense social support for irrigated agriculture due to its perceived economic benefits (De Stefano and Lopez-Gunn 2012). This idea gained traction in the early days of this production model when greenhouses were small family businesses that provided employment to local individuals and distributed wealth more evenly. However, over time, the price of agricultural land has skyrocketed, increasing by 62% in the past decade in Almería (Junta de Andalucía. 2023a, 2023b). As the treadmill theory predicts, each round of investment weakens the employment situation for workers, worsens environmental conditions, but boosts profits for investors.

Farmers find themselves trapped between two opposing forces that exert intense pressure, leaving them with limited options. On one hand, large distributors impose their terms regarding harvest volume, product type, and price. The fragmented cooperative model of Almería, with 141 marketing organizations (Juntti and Downward 2017), weakens farmers' bargaining power and force them to accept unfavourable deals and bear all the risks. In a way, those who continue farming become de facto employees of these large distributors. Recent studies (Capdevila 2023) demonstrate that this situation leads to mental exhaustion due to stress and lack of free time resulting from the delicate balance between allocating time to grow the farming business for economic profitability (Wojewódzka-Wiewiórska et al. 2020).

On the other hand, the production model becomes increasingly reliant on external inputs, driven by environmental degradation and the sector's high level of technification. Only a few companies produce these inputs, granting them significant bargaining power.

This tightening siege is exemplified by the concentration of the entire production process in the hands of a few dominant agents. This process, known as the "uberization of Spanish agriculture" (COAG 2019), subjects farmers to burdensome indebtedness while an imbalanced food chain leaves substantial profits in the hands of actors other than the farmers. These actors, such as input suppliers, brokers, intermediaries, wholesalers, exporters, and retailers, accumulate capital and use it to compete with farmers in a detrimental spiral of competition—a manifestation of the Treadmill of production in action.

Regarding the labor market, it is evident that employment opportunities are being created, but unfortunately, they are largely characterized by poor quality. Until recently, the increasing seasonal migrant labor consisted predominantly of undocumented workers with reduced (or lacking of) labor rights (Aznar-Sánchez and Galdeano-Gómez 2011). Despite many greenhouse owners legalizing their workers and providing stable year-round employment (there are 74,674 workers affiliated with social security) (Fundación Cajamar 2023b), there are still distressing situations that frequently come to light through media coverage (Lawrence 2011; de Pablo et al. 2020; Sánchez 2023). Some authors even describe these circumstances as "modern slavery" (Chesney et al. 2019; Rippingale 2019) (Fig. 3B). The combination of low wages, long working hours, and inadequate housing conditions (with dozens of shantytowns housing thousands of people in extreme need) (Fundación Cepaim 2018) for many workers paints a starkly different reality compared to the perception of an "Almerian Miracle". A significant number of workers (women comprises 90% of the workforce) express dissatisfaction with harsh working conditions (including workdays lasting 12 to 16 hours) (Villaverde 2017), wages below the legal minimum (García 2022), and the prevalence of temporary contracts, which affect 70% of workers (Villaverde 2017).

As the region's resources continue to be degraded, the reliance on external inputs has surged (Fig. 3A). The mounting energy prices have exposed the vulnerability of this industrial agriculture model. A prime example is the temporary closure of Fertiberia, Spain's major nitrogen fertilizer manufacturer, prompted by the escalating energy costs (Agencia 2022), posing a significant threat to the system. Similarly, the supply of phosphorus is heavily dependent on a limited number of suppliers, with approximately 85% of the world's remaining high-grade phosphate rock concentrated in just five countries, including Morocco, with 70% of the total (Martín-Ortega et al. 2022). Additionally, groundwater degradation has left the province reliant on external water sources or the construction of costly desalination plants, which surpasses the expense of traditional irrigation systems (Martínez-Alvarez et al. 2016).

The increase in production costs carries two important consequences. Firstly, investors seek more favorable locations for their investments in response to these challenges. Secondly, it exacerbates the treadmill spiral, leading to an influx of inexpensive products that are discarded before even entering commercial distribution channels due to their low market value (Martínez-Valderrama et al. 2020a) (Fig. 3C).

3.2 Treadmill Globalization

The globalisation of groundwater use since the mid-twentieth century, often referred to as the "silent revolution" (Llamas and Martínez-Santos 2005), was driven by a convergence of technical, political and economic factors (Foster and Chilton 2003). The economic implications of harnessing this resource are particularly noticeable in the drylands, where the socio-economic transformation is often referred to as a "miracle" (Postel 1999). However, these miracles are short-lived, given the low or even negligible recharge rates, which have led to the depletion of these aquifers (Famiglietti and Ferguson 2021), posing a major threat to the survival of the socio-ecosystems they support.

Under the Green Morocco Plan, the production of high-value agricultural export has been promoted (Tanchum 2021). Thus, by 2022, it has supplied more horticultural produce to the Spanish market (worth 850 M€) than Almeria (740 M€) (León 2023b), our case study, which had been leading this market for years. The growth of this area, monitored with satellite image data (Bazza 2018), confirm the exponential behaviour of the phenomenon. In the last two decades it has increased from 9000 to 26,000 ha (León 2023b) just in the Souss-Massa-Draa region (south of the High Atlas, whose capital is Agadir). Greenhouses have already spread to the provinces of Kenitra and Larache (NE Morocco, with more than 8500 ha (Fernández 2018), and another 5000 new hectares are expected in Western Sahara, in what has been called the "Tomato Megalópolis", an ambitious plan promoted by large business groups aiming to create one of the largest tomato production centres in the world (Ponce 2021). The consequences of this rapid expansion are the degradation of groundwater resources (Hssaisoune et al. 2017; Benabderrazik et al. 2021), and poor working conditions driven by the quest for large short-term profits (Murias and García-Luengos 2021).

In Biskra (Algeria), located on the edge of the Sahara desert, the rapid expansion of commercial palm groves (some 43,000 ha), and intensive horticulture (17,365 ha in 2014, of which 4900 ha are greenhouses) (Petit et al. 2017) has made the area (with more than 100 kha of irrigated land) (Khomri et al. 2022) a place of remarkable economic development and the main supplier of fruit and vegetables to the national market. This development has meant a shift from traditional practices characterised by small fields collectively managed through community irrigation systems, to a massive use of groundwater in the hand of private capital served by powerful tube-wells (Kuper et al. 2016) (by 2014 only about half of them were officially authorized) (Petit et al. 2017). Signs of deterioration, in the form of soil salinization (Abdennour et al. 2021) and decreasing groundwater levels (Khomri et al. 2022), have not been long in coming. In NW China the fast transition from food crops to cash crops, when in the early 1980's farmers were given more autonomy in land use, is driven to groundwater depletion (Zhang et al. 2014). The hyper-arid region of Ica (SE Peru, < 10 mm yr^{-1}) has evolved rapidly since the late 1990s into the most advanced agricultural development in the country. The political reforms of the Fujimori administration allowed foreign investments in the country (Díaz Rios 2007). As a result of investments, big agro-exporters have the latest methods and technology available, thus producing asparagus of a consistent high quality (an export industry worth about 6000 M$ yr^{-1}) (Fernández-Escalante et al. 2020). The intensive use of waterwells for year-round irrigation is the reason of enrinchment and grondwater degradation. The Arabian Desert has also seen a boom in groundwater use, and its collapse (Martínez-Valderrama et al. 2020b), and in California large groundwater withdrawals, combined with minimal oversight, have led to aquifer overdraft and concomitant groundwater depletion (Jasechko and Perrone 2020).

4 Replacing the Logic of Markets by the Logic of Nature

The traditional use of water resources in drylands has been characterized by sustainable practices subdued to the cycles of nature that resulted in subsistence economies (De Haas 2011). Technological advancements have overcome natural scarcity, leading to powerful economies based on groundwater exploitation and suitable temperatures. However, in many cases, these "miracles" are ephemeral, and after a short period of prosperity, land degradation restricts management options (del Barrio et al. 2021). Paying more attention to market signals than to those of land depletion has led to the collapse of water resources, i.e., desertification, of many of these areas.

4.1 Dismantling the Treadmill

Water demand management measures must be prioritized in Almería, as required by the EU Water Framework Directive (European Commission 2000). The sustainability of irrigated agriculture relies heavily on a key measure: reducing and containing its surface area (Deines et al. 2020). This can be accomplished by emphasizing product quality over production volume. By doing so, the inclination to mass-produce large quantities of crops, which leads to price devaluation, can be diminished. To attain favorable prices that enable quality production, it is essential to enforce the food chain law (BOE 2021), which aims to establish a fairer relationship among farmers, the industry, and distributors. Strengthening the bargaining power of farmers in relation to major distributors is crucial to increase the value of their products. The formation of large cooperative groups would consolidate their negotiating position.

Water demand management includes pricing mechanisms in aim to reduce water use (Toan 2016; Suárez-Varela 2020). Water pricing policies have been successfully implemented in urban water consumption management in Spain for decades. However, their effectiveness has been less pronounced in the agricultural sector, largely due to negative industry reactions and potential electoral consequences (Picazo-Tadeo et al. 2020). Consequently, since the enactment of the 1985 Water Law (BOE 1985) to the present day, measures have consistently been taken to establish "social prices" for agricultural water use, often accompanied by direct subsidies funded by the state budget (WWF 2015). Implementing progressive tariffs based on consumption should be a prominent consideration for managing water use in agriculture (Aldaya and Llamas 2012).

Another mechanism could be the introduction of water cost compensation mechanisms between the city, which can pay higher prices, and the countryside, which would benefit from price "support" from the urban environment. This type of mechanism is already used in some places in Spain, such as in the region of Marina Baja (Alicante) where farmers receive purified water with advanced treatments for crop irrigation at affordable prices, due to the payment of the wastewater treatment fee by the city of Benidorm (Gil Olcina and Rico Amorós 2015).

Furthermore, a portion of irrigated land should be transitioned to crops that are more suitable for the region's natural arid conditions (Nabhan et al. 2020). Thus, profitable alternatives must be explored. Considering that the crops being replaced are primarily cash crops intended for export, it is unlikely that replacing a portion of them would adversely affect the region's food security. There are lucrative options in the cosmetic and medicinal markets (Navarro-Rocha et al. 2023), and aromatic plants, that provide additional ecological services (Durán-Zuazo et al. 2008). it is worth considering replacing a portion of intensive fruit and vegetable crops with rainfed species, complemented by partial irrigation. This shift aligns with an agricultural model that emphasizes quality and encourages the cultivation of native varieties. (Martínez-Fernández 2021).

. Given that 99% of greenhouses already utilize localized irrigation (Valera et al. 2016), there is limited room for enhancing water use efficiency. However, the adoption of smart agricultural techniques, which considers factors such as evaporative demand, phenological stage, and other relevant variables to ensure the optimal allocation of resources to the plants (Karanisa et al. 2022), can further optimize water and fertilizer usage by precisely addressing the specific requirements of the crops at any given time.

4.2 Reducing Water and Energy Dependence

Desalination and reclaimed waters have the potential to reduce dependency on groundwater. Currently, Almería has nine desalination plants, which supply 14% of the water used in agriculture (Junta de Andalucía. 2016). These plants have a combined treatment capacity of 106 $hm^3\ yr^{-1}$, including 9 $hm^3\ yr^{-1}$ sourced from brackish groundwater, exclusively for agricultural use (Junta de Andalucía. 2023a, 2023b). As the infrastructure connecting these plants to the irrigation communities has been developed, water supply currently provides 24.5 $hm^3\ yr^{-1}$ for irrigating 18,500 ha (Martínez-Álvarez et al. 2019).

Reclaimed water is an increasingly used resource, especially in arid and semi-arid climates like the Mediterranean (Giannoccaro et al. 2019). Almería has a potential reuse capacity of 70 $hm^3\ yr^{-1}$ (Junta de Andalucía. 2023a, 2023b), which matches the volume of urban and industrial wastewater generated in the area. If properly treated, this amount of water could replace up to 40% of the current groundwater consumption for agricultural use, underscoring the importance of improving treatment facilities and infrastructure to achieve sustainable water resource management. A recent report (Megías Baños 2021) revealed that only 54% of Almería's wastewater treatment plants comply with the European treatment directive. Expanding its use (a new wastewater treatment plant has recently been commissioned, which will supply 14 $hm^3\ yr^{-1}$ of water to agriculture (La Voz 2023)) would be a significant step towards reducing groundwater use while achieving a more circular economy.

Finally, ecological restoration in the headwaters of watersheds using plant species appropriate to their aridity, soil and state of degradation conditions, can increase aquifer recharge in the medium to long term (Norman et al. 2022). Aquifer recharge can also be achieved by means of dams that collect part of the torrential rains typical of drylands (D'Odorico et al. 2019). To this end, the beds of wadi beds and the apical zones of large alluvial fans have been proposed as potential recharge areas (Boer et al. 2001).

Faced with the inevitable deterioration of groundwater, desalination plants are being touted as a renewed solution. Nonetheless, such measures perpetuate the existing water supply model, contributing to the widening water gap (Martínez-Valderrama et al. 2023b). the promotion of desalinated water contributes to increased energy demands in the region. Utilizing 16.8% of desalinated seawater would result in a 32.4% rise in energy consumption and a 19.6% increase in GHG emissions. Furthermore, a higher usage rate of 26.5% (desalinated seawater) would lead to even larger impacts, with energy consumption rising by 50% and GHG emissions increasing by 30.3% (Martin-Gorriz et al. 2014). To mitigate emissions, solar energy emerges as a promising solution in Almería and other dryland areas. However, the widespread deployment of photovoltaic plants presents additional concerns such as habitat destruction (Valera et al. 2022). Once again, effective land use planning becomes crucial in achieving sustainable development by harmonizing various land uses (Li 2022).

4.3 Pedagogy for the Dominant and Misleading Narrative

The prevailing model of agricultural irrigation in drylands is built on several misconceptions. While irrigation may offer development opportunities in an economic sense, it does not serve as a physical barrier against land degradation and desertification but rather may enhance it. Desertification itself does not refer to the encroachment of the desert, but rather to land degradation resulting from human activities and climatic variations (UNCCD 1994). Paradoxically, increasing water use efficiency leads to greater water consumption, resulting in groundwater degradation, and collapse of unique dryland ecosystems, such as iconic cases including wetlands in Doñana and Tablas de Daimiel National Parks (Martínez-Santos et al. 2018; Camacho et al. 2022). The first necessary step to recover these ecosystems and to prevent them to be degraded further is reducing the irrigated area.

Likewise, greenwashing strategies have gained popularity, as companies seek to gain consumer approval through deceptive food labeling. While well-designed labeling can promote genuinely sustainable production, certain companies neglect significant environmental impacts and instead use environmentally friendly practices as a business strategy to gain a competitive advantage, i.e., they reinforce the Treadmill through the step 1. For instance, labeling products as environmentally friendly due to the use of biological pest control and reduced chemical fertilizer use (although they comply with current legislation) ignores the detrimental effects on groundwater resources resulting from their production activities. Arguments that greenhouse structures mitigate erosion in semi-arid regions are also questionable, considering the loss of biodiversity they entail.

5 Conclusions

In an urbanizing world influenced by climate change and its uncertain consequences, rethinking our approach to food production becomes crucial to address ongoing environmental degradation, mitigate climate change and sustain a growing population. The model of large-scale production driven by the substitution of labor with capital-intensive technologies and infrastructure, which has become prevalent in many dryland regions, has resulted in widespread degradation of groundwater resources and associated socioeconomic systems. We have used the lens of the Treadmill of production theory, we have identified the underlying foundations of this exploitative and profit-driven production model.

Our analysis offers insights into the key areas that need to be reimagined to transform transient wealth models based on the exploitation of groundwater resources into catalysts for sustainable development in drylands. The proposed measures, starting with the containment of irrigated land and promoting local water and energy sources, aim to challenge dominant and misleading narratives. Moreover, these efforts should be based on a paradigm of water demand management through territorial planning, as it is the only means to prevent irreparable long-term consequences.

Despite the acknowledged degradation of groundwater worldwide, the use of these resources continues to be planned for political reasons (such as self-sufficiency in Iran or Saudi Arabia), or market reasons (such as the recent changes in China and the capitalist logic of maximising profit in the short term of Western economies), leaving aside the rhythms of nature and the enormous uncertainty brought about by climate change. The transition from market logic to natural logic cannot be abrupt. It must be planned and implemented progressively through regulations approved by governments (state and regional in Spain). Hydrological planning documents (river basin plans) and land-use planning documents (regional and sub-regional land-use plans) must play a decisive role here. But it is necessary that, in the face of the territorial and environmental imbalance generated by the uncontrolled expansion of intensive irrigation, legal measures and legally approved regulatory planning (hydrological and territorial) must be enforced. Ultimately, it is essential to regulate power dynamics within the territory, where a few individuals profit immensely from the unsustainable exploitation of a shared resource.

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Data Availability The data presented in this study are openly available in FigShare at https://figshare.com/s/4e8cfc5fb9ad6c6f02b9.

Declarations

Conflict of Interest This research does not have no conflict of interest. The authors have no competing interests to declare that are relevant to the content of this article.

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