How greenhouse horticulture in arid regions can contribute to climate-resilient and sustainable food security

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How greenhouse horticulture in arid regions can contribute to climate-resilient and sustainable food security

Simon Goddek[a,i], Oliver Körner[b,*], Karel J. Keesman[a], Mark A. Tester[c], Ryan Lefers[c], Luuk Fleskens[d], Alyssa Joyce[e], Erik van Os[f], Amit Gross[g], Rik Leemans[h]

[a] Mathematical and Statistical Methods (Biometris), Wageningen University, P.O. Box 16, 6700, AA, Wageningen, the Netherlands
[b] Next-Generation Horticultural Systems, Leibniz-Institute of Vegetable and Ornamental Crops (IGZ), Theodor-Echtermeyer-Weg 1, 14979, Grossbeeren, Germany
[c] Division of Biological and Environmental Sciences and Engineering, Center for Desert Agriculture King Abdullah University of Science and Technology, Thuwal, Kingdom of Saudi Arabia
[d] Soil Physics and Land Management Group, Wageningen University & Research, P.O. Box 47, 6700, AA, Wageningen, the Netherlands
[e] Department of Marine Science, University of Gothenburg, Carl Skottsbergs gata 22 B, 413 19, Gothenburg, Sweden
[f] Business Unit Greenhouse Horticulture, Wageningen University and Research, Wageningen, the Netherlands
[g] Department of Environmental Hydrology and Microbiology, Zuckerberg Institute for Water Research, Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Beersheba, Israel
[h] Environmental Systems Analysis Group, Wageningen University and Research, Wageningen, the Netherlands
[i] Brownstone Institute, 2028 E Ben White Blvd, #240-3088, Austin, TX, 78741, USA

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ABSTRACT

A potential change in climate and temperature could strongly affect weather-related crop losses. Using wastelands to grow crops in controlled greenhouse environments could improve global food security and preserve ecosystems. However, the impact of climate change on additional energy and water requirements of greenhouse-horticulture food production is still unknown. Using a greenhouse simulator for four locations (The Netherlands, Spain, Saudi Arabia and Namibia), we show that a rise in outdoor temperatures can be counterbalanced with a more intensive water-based cooling. Between 6.9% and 17.9%, more water is required in the worst-case scenario in the year 2100, while the yield quantity decreases by 3%–6% due to slightly deteriorating growth conditions within the greenhouse. Since cooling systems consume up to 90% of the total water use in desert greenhouses, saltwater cooling could play an essential role in increasing the efficiency and sustainability of greenhouse horticulture systems in arid regions. In this study, we investigate the economic and technical feasibility of such greenhouse systems on a larger scale and show the massive potential of these systems. The developed scenarios demonstrate considerable climate resilience, enabling the cultivation of fresh vegetables in arid and infertile regions both presently and in the future.

1. Introduction

Anthropogenic influences, such as deforestation, are causing alterations in micro-climates, leading to more substantial impacts on soil fertility and agricultural land than previously anticipated (Campbell et al., 2016; Rosenzweig and Parry, 1994; Zhang and Cai, 2011). This issue will further aggravate global water problems and pose particular challenges for the agriculture sector as well as increase food distress, especially in arid and semi-arid regions (Masson-Delmotte et al., 2018). These regions make up more than one-third of the world's landmass and are inhabited by approximately one-fifth of the Earth's human population (Sivakumar et al., 2005).

Even as more food needs to be produced, agricultural land is inherently limited to roughly one-quarter of the world's land surface. Nevertheless, the availability of agricultural land is decreasing due to soil erosion and nutrient depletion in soils or lack of irrigation (Borrelli et al., 2017; Jones et al., 2013). Particularly near population centres, suitable and affordable land for agriculture is limited. With the projected population growth, per-capita arable land is estimated to almost halve before the end of this century (Conforti, 2011). This decline is similar to

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* Corresponding author. Leibniz-Institute of Vegetable and Ornamental Crops (IGZ), Theodor-Echtermeyer-Weg 1, 14979, Grossbeeren, Germany.
E-mail addresses: simon@goddek.com (S. Goddek), koerner@igzev.de (O. Körner), karel.keesman@wur.nl (K.J. Keesman), mark.tester@kaust.edu.sa (M.A. Tester).

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the space required for urban expansion (van Vliet et al., 2017). In addition to these urbanization effects, increased global food demand has led to large-scale deforestation, particularly soy, cattle, and palm-oil production (Wicke et al., 2011).

Three possible ways emerge to meet future food demand based on projected population growth. First, food waste and post-harvest losses should decrease (Godfray et al., 2010). Second, food production should increase through increased productivity per unit of land or new land developments (Howden et al., 2007). However, the worldwide availability of new agricultural land is marginal. This renders this option less plausible. Third, a shift towards a plant-based diet could increase the resource use-efficiency of existing agriculture (Carlsson-Kanyama and González, 2009; Stehfest et al., 2009), However, it is important to consider that an inadequately planned plant-based diet could lead to nutritional deficiencies and associated health issues, and thus, a balanced approach is recommended to maintain overall health and well-being. This is, in particular, relevant for fresh vegetables in hot and arid zones near population centres concerning healthy eating choices, reduction of transportation costs, and spoilage.

Several studies showed that greenhouse systems provide an essential solution for growing fresh vegetables in hot, arid regions (Choab et al., 2019; Ghoulem et al., 2019; Goddek and Körner, 2019) as such systems can make use of otherwise unusable land to produce high-value crops. Furthermore, extending such systems in terms of area, especially in populous (peri-) urban environments, can further facilitate the recycling of water and nutrients. However, to what degree a potential change of climate affects water, thermal energy and electrical requirements of such greenhouse systems in moderate and hot regions remains unclear. To date, this has not yet been assessed. This study explores the potential of industrial-scale greenhouse horticulture in arid regions near population centres, concerning the above-mentioned performance indicators of water and energy under climate change. This paper uses a numerical modular simulation model for greenhouse systems to compare virtual greenhouse setups in Spain (Almeria), and the Namib (Namibia) and Arabian (Saudi Arabia) deserts in three periods ‘now+10 years’, 2040–2049 and 2090–2099 with respect to the four IPCC’s future climate-change scenarios as published as the *Representative Concentration Pathways* (RCPs) in the CMIP5 multi-model ensemble by the European Network for Earth System Modelling (ENES, 2020; van Vuuren et al., 2011). Regarding technological and energy requirements (thermal and electrical), water use efficiencies, and yield expectations for tomatoes, the Dutch (Westlands) greenhouse climate zone serves as a control case.

2. Desert farming: making arid regions arable

A variety of technological solutions for cultivation in arid regions have emerged from more traditional farming strategies. Historically, oases have been prominent centres of cultivation, where various water harvesting techniques facilitated to grow trees and crops (Dile et al., 2013; Fleskens et al., 2007; Schiettecatte et al., 2005). Due to possible climate-change-induced aridification, regions like sub-Saharan Africa, the Middle East, and South Asia are more frequently facing less predictable agricultural productivity (Epule et al., 2017). To counteract this tendency, more water is required to keep the soil moist. Water harvesting probably helps to overcome some of the increased aridity, but its potential is limited (Lebel et al., 2015; Rockström et al., 2010). Also, extraction of groundwater or water from fossil aquifers is practised, but this is mostly unsustainable (Al Naber and Molle, 2017). Countries in the Middle East and North Africa, for instance, are currently depleting their aquifers at an alarming rate (Mazzoni et al., 2018).

Apart from irrigation, most desert soils also lack nitrogen, and this makes these regions largely infertile. Traditional farming methods have compensated by adding manure in planting pits or by delivering nutrients from upstream watersheds in irrigation systems (Tesfai and Sterk, 2002). Besides, excessive fertilization and land exploitation increase land degradation and reduce the available arable land (Joyce et al., 2019). Possible mitigation strategies include reforestation of semi-arid regions such as the Sahel (Goffner et al., 2019). However, local stakeholders are still succeeding in upholding their interests at the expense of nature and climate (Sauer, 2018; Simon, 2019). Another approach to cope with harsh climatic conditions is the breeding and selection of drought and saline tolerant plant species (Dhankher and Foyer, 2018). Unfortunately, this approach does not tackle the root causes of desertification, even though it might alleviate some of its symptoms.

Israelites have traditionally had to cope with both water scarcity and extreme temperatures. They identified greenhouse horticulture as an agricultural approach that has a high nutrient and water use efficiency (Linker et al., 2011; Tal, 2007). In such systems, climate conditions can be carefully regulated. This approach has also been commercially implemented in other arid regions, such as the Australian Sundrop Farms, where tomatoes grow in soilless (i.e. hydroponics) greenhouses with desalinated seawater that is used to both cool and irrigate plants (Hitchin, 2014). Hydroponics in semi-closed or closed greenhouse systems likely reduce plant-specific evapotranspiration rates, and allow (partial) water recovery through condensation (Kloas et al., 2015). The Dutch initially developed these systems to cope with polluted European soils that could not be restored to meet agricultural standards. Hydroponics also constitutes one of the best available technologies to save freshwater in arid regions and simultaneously increase productivity with fewer fertilizer inputs (Treftz and Omaye, 2016).

2.1. Advantages and disadvantages of desert greenhouse farming

Several benefits of arid greenhouse farming are apparent, but some specific limitations emerge, primarily in response to its harsh arid and consistently hot environments (see Table 1). For instance, arid greenhouses have few problems with adequate solar irradiation, but instead, their cooling and humidity management is challenging (Campen et al., 2018). Many greenhouse technologies are developed for temperate climates, where greenhouses allow for year-round crop production under varying seasonal conditions. Managing greenhouses for a seasonally variable climate is more complicated than production in more constant conditions of an arid environment. However, the necessity to improve water use and manage evapotranspiration becomes increasingly essential in these consistently hot environments. Desalination technology is often needed to provide adequate freshwater, while the salt brine as a waste product of the desalination process requires treatment to avoid unnecessary environmental contamination.

In hot environments, cooling of greenhouses is thus challenging (Tsafaras et al., 2021). In addition to freshwater for the plants, evaporative cooling systems also require a (fresh-)water source (Sabeh et al., 2011), and evapotranspiration rates are higher under conditions of high irradiation (Stanghellini and Van Meurs, 1997). Managing humidity is thus important. Lower relative humidity levels outside the greenhouse increase the effectiveness of evaporative coolers, similar to the commonly used ‘pad & fan’ cooling systems, but the substantial diurnal temperature variations in desert environments necessitate a greater range of cooling and heating capacities, as well as careful greenhouse design to manage both heat loss during the day and heat retention at night (Hemming et al., 2017; Körner, 2019; Vanthoor et al., 2011). A large share of water consumption of a desert-based greenhouse in hot conditions will be the result of crop evapotranspiration and plant organ fresh weight increases (fruit, leaves, stem). Water consumption of vegetables in areas with high irradiation benefits from maximizing water recirculation and if possible, recycling of waste streams within the system. The ability to recycle water effectively makes aquaponics technologies (i.e. the combined integrated cultivation of hydroponics crops and aquaculture species) ideally suited to this environment given it results in the production of both fish and crops in a beneficial relationship that recovers both water and nutrients. For instance, the same amount of water is used in hydroponics or aquaponics operations, despite the

Table 1

Overview of advantages and restrictions of arid greenhouse farming.

Factor	Advantages of Arid Greenhouse Farming	Disadvantages of Arid Greenhouse Farming
Greenhouse Horticulture	● Possibilities for high degree of nutrient and water use efficiencies (Tsafaras et al., 2021; Xie et al., 2018)	● Costly and a high degree of technical competence is required (Sabeh et al., 2011) ● A large body of historical know-how exists for greenhouses in temperate climates, while greenhouses in hot semi-arid climates are still in its infancy ● Possible material degregation in harsh climates (Baeza and Kacira, 2017)
Solar Radiation	● High energy availability for energy production and water desalination (Achour et al., 2021; Bicer et al., 2022) ● Possibility to create synthetic nitrogen fertilizer (Haber-Bosch process) (Smil, 2004) ● To a certain level, depending on temperature and CO_2 concentrations, photosynthesis is enhanced and thus increases crop growth rates	● Often correlated with hot climate; increased cooling capacities required (Willits, 2000) ● High temperatures and solar radiation can reduce the lifespan of greenhouse construction materials
Water Availability	● Innovation driver (Mendoza-Fernández et al., 2021)	● Crops and cooling systems usually require fresh water (Sabeh et al., 2011) ● Water availability in arid regions is usually limited ● Energy-intensive desalination technology is often required to get fresh water (Aznar-Sánchez et al., 2019) ● Desalination is limited to sea- and brackish water availability (Al-Ismaili and Jayasuriya, 2016) ● The by-product of the desalination process, a salty brine, might need to be post-treated to avoid unnecessary environmental pollution (Ahmad and Baddour, 2014)
Biocontrol	● There are generally lower threats of pests and diseases in hot semi-arid climate zones ● Resilient towards locust plagues and insect infestations.	
Arid Climate	● Lower relative humidity increases the cooling effect of pad & fan cooling systems (Franco-Salas et al., 2019)	● Usually, considerable differences of temperature between day and night; i.e. high cooling and heating capacities are required (Abdel-Ghany et al., 2012)
Economics	● Vast land resources, often with no competing use, resulting in low land costs ● High quality produce in a non-competitive economic environment	● Usually poor infrastructures ● Often far away from primary sales markets (Weiss et al., 2018) ● Being far from the market, food processing could be necessary
Land Use	● Very often no competing land use ● Increase in the total amount of global arable land due to climate-controlled environments ● Because arid land is usually vacant, there are no costs associated with land redevelopment, only minimal land preparation and construction	●Bare-surface land near the greenhouse can lead to dust storms and requires frequent greenhouse cleaning (Baeza and Kacira, 2017) ● Possible need for green barriers to accommodate the microclimate around the greenhouse
Local employment	● Creates agricultural employment opportunities in agriculture, agri-services, food processing and greenhouse construction where traditionally very few job opportunities existed	● Local population requires significant training because of a lack of related historical agriculture experience (Panwar et al., 2014)

additional fish production (Goddek et al., 2019; Yep and Zheng, 2019).

Pest and disease pressure in many agricultural systems leads to lower quality products and intensive use of pesticides and fungicides (Körner and Challa, 2003; Singh et al., 2016). Greenhouse systems in desert regions have lower disease risks than conventional open-field agriculture and greenhouses in more humid climates (van Bruggen et al., 2016). In the harsh desert environment, mainly niche organisms adapted to such extreme climates will be present, thus reducing the risks of interface with both temperate and sub-tropical/semi-arid greenhouse-grown crops. However, it remains that pests and diseases can be introduced through imported material, and as such, strict control of imports of, e.g., seeds are needed. Vast desert land resources, often with no other competing uses, also result in low land acquisition costs (Xie et al., 2018), and nearby markets often have high demands for fresh products that would otherwise need to be imported (Karanisa et al., 2021).

Three environmental factors condition the feasibility of greenhouse crop production: (1) moderate temperature without significant diurnal or seasonal fluctuations; (2) sufficient daily solar irradiation (i.e. optimal daily light integrals); and (3) freshwater availability (Ghani et al., 2019). The more the ambient environment deviates from these conditions, the more costly and complex the mitigation strategies (Van Straten et al., 2000). To overcome these obstacles, economically feasible technological solutions for supplementary lighting, cooling/heating, and desalination and/or water reuse might need to be considered (Fig. 1).

3. Methodology

We explore high-tech greenhouse horticulture's economic and technical potential in desert areas concerning the key performance indicators (KPIs): water use efficiencies, thermal, electrical energy requirements, and crop productivity. As benchmarks, we focus on production systems in two existing locations with substantial greenhouse production (i.e. the Dutch Westlands and Spanish Almeria) and the widely discussed cases of closed environments using the concept of so-called plant factories. We simulate greenhouse systems to compare virtual greenhouse systems in the Namib (Namibia), and Arabian (Saudi Arabia) deserts for the current situation (i.e. 2019) and both in 2050 and 2100 (for four IPCC's future climate-change scenarios) in terms of water usage, technology and energy requirements (thermal and electrical), and harvest expectations for fresh tomatoes (as tomatoes are the primary greenhouse products in the Dutch Westlands and Almeria).

We used a well-validated and widely applied greenhouse simulator for the scenario analyses with actual (2019) and model-predicted hourly outside climate variables for the years 2050 and 2100 (see Section 3.2) (Körner and Hansen, 2012). The greenhouse simulator, which we further describe in Section 3.3, is based on a *digital twin* of existing greenhouses. The modular nature of the simulator enables to adjust for different types of physical greenhouse equipment. To better compare locations and future scenarios, we designed a standard 5 ha Dutch-type greenhouse with different technical solutions to control the climate to create suitable cultivation conditions for all four physical locations. The four locations reflect the differences in climate and availability of water in terms of groundwater, brackish water, or seawater. In addition to the

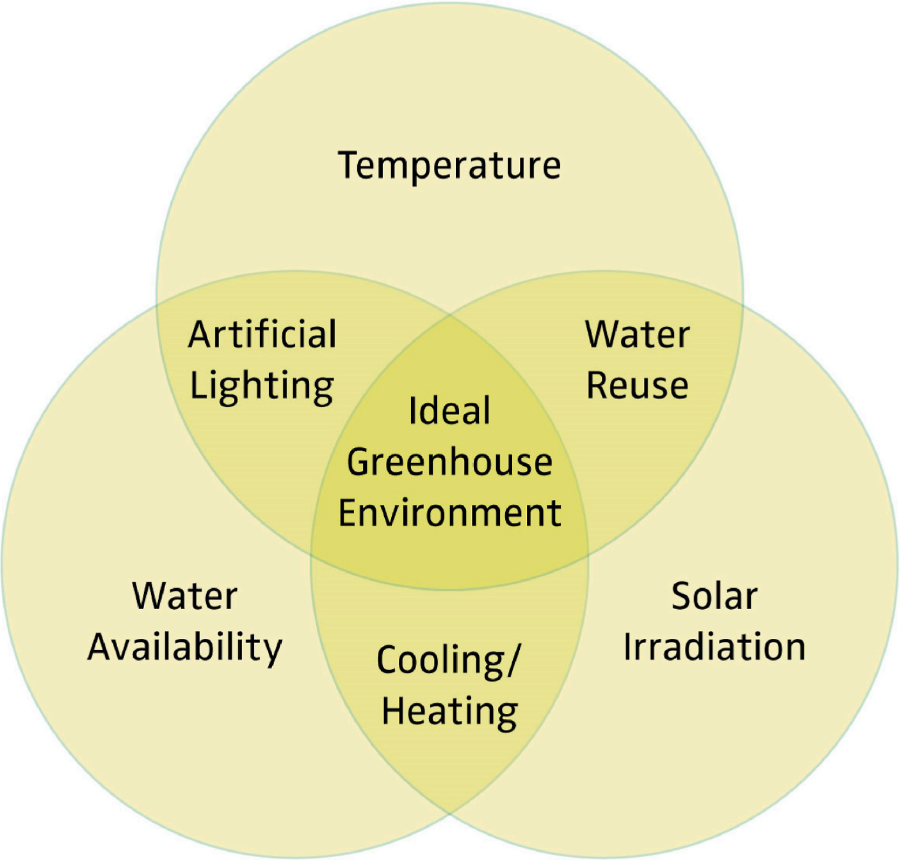

Fig. 1. Ideal Greenhouse Environment for vegetable cultivation. For instance, a greenhouse in an environment with moderate temperature and solar radiation and a lack of water requires a high degree of water reuse.

KPIs mentioned above, we also assess the possible climate change impacts on productivity and water requirements of arid greenhouse systems.

3.1. *Case study locations and justification*

Three arid regions with potential of serving as desert-agriculture sites were identified based on their climatic conditions and their access to water (groundwater, brackish water, seawater), ranging from a desert like cimate on the existing greenhouse production area (Almeria Peninsula, Spain), via dry and semi-hot climate (Namib, Namibia), and hot and humid without rain (Arabian Desert in Thuwal, Saudi Arabia).

Almería Peninsula (El Ejido, Spain; 36°46′59″N 2°49′00″W): This desertified peninsula in the municipality of Almería, which lays 30 km west of the city, is the driest region of Europe and is the only catalogued desert in Europe. Developing intensive agriculture under plastic around El Ejido has been a principal regional economic driver (Torrellas et al., 2012; Valera et al., 2017). The area is influenced by hot and dry African winds that cause periodic temperatures higher than 37 °C with high radiation in summer and apparent seasonal differences (peak at 1200 Wm^{-2}; 55% difference between peak radiation of highest and lowest month; a daily light integral of 8–79 mol m^{-2}). Traditionally, the area was used for grape production, which was gradually replaced by greenhouse production in the 1960s. Until the early 2000s, the greenhouses of the Almería region were not designed or adapted to its climatic conditions, wherein the simple plastic structures did not deal effectively with low temperatures on winter nights, high temperatures during the day, or the higher humidity at night (Castro et al., 2019; de Pablo Valenciano et al., 2019). Winds, low water quality (brackish and saltwater), and water shortages have compounded these problems (Torrellas et al., 2012). Around 80% of the resources come from underground aquifers (Custodio et al., 2016), and the remaining 20% from transfers, seawater desalination plants, reservoirs and regeneration plants for purified water (Luis Caparrós-Martínez et al., 2020). In Almeria, both cooling and heating are necessary to achieve optimized yields for year-round production (Franco-Salas et al., 2019).

Namib Desert (Swakopmund, Namibia; 22°38′41.4″S 14°41′33.5″E): the Namib Desert is the geologically oldest desert in the world and stretches along the Atlantic coast of Namibia, and can be regarded as extremely arid (Liu and Zhou, 2021). Namibia is considered to be one of the countries that are most vulnerable to climate change (Somses et al., 2020). The case study is situated 15 km inland in a semi-dry desert region with high solar radiation throughout the year (peak at 1200 Wm^{-2}; less than 30% difference between peak radiation of highest and lowest month; a daily light integral of 25–80 mol m^{-2}) and access to brackish groundwater (EC of 12 mS cm^{-1}) as well as access to the public water supply. The Benguela current along this coast promotes moderate temperatures. However, continental eastern autumn winds can cause periodic temperatures of up to 42 °C. The area is sparsely cultivated and is traditionally used for either extensive cattle grazing or has simply been abandoned due to the harsh climatic conditions (Kaurivi et al., 2021a, 2021b).

Arabian Desert (Thuwal, Saudi Arabia; 22°18′44.7″N 39°05′55.7″E): the Arabian Desert encompasses nearly all of the Arabian Peninsula in western Asia. Agricultural production that played an essential role for human nutrition in this region is threatened by climate change (Karanisa et al., 2021). While the majority of the Arabian Desert experiences hot and dry (non-humid) conditions (Kareem et al., 2022), coastal areas along the Arabian Gulf and the Red Sea are hot and humid, despite the lack of rainfall (Hasanean and Almazroui, 2015; Patlakas et al., 2019). The chosen study location is near Thuwal on the Red Sea coastal sabkha flat. The site has access to a Red Sea beach well (EC of 55 mS cm^{-1}) and to freshwater from a reverse osmosis desalination plant. Peak solar radiation is around 1000 Wm^{-2} (Alwadei et al., 2022) while temperatures during the hottest and most humid months average at near 38 °C with relative humidity around 55% at solar noon. Occasional winds from the dry peninsula may lead to temperatures up to 50 °C with little to no humidity, while dust is a regular pattern in the Saudia Arabian peninsula. Today very little agriculture occurs in the area, except for small-scale sheep, goat, chicken, and camel farms, where the bulk of animal fodder is imported from other regions.

Westlands (De Lier, The Netherlands; 51°58′07.0″N 4°13′40.1″E): The moderate climate of this Dutch coastal region has peak temperatures of 29 °C in summer and occasional low freezing temperatures below −10 °C in winter. This variability motivated the establishment of a greenhouse-production industry from the 1950s onwards (Van Der Velden, 1988). Due to the coastal location, solar radiation in this area is higher than inland. However, although this region is the most productive greenhouse region in Western Europe, its climate is not optimal (Pluimers et al., 2000). In summer, local solar radiation tops with 940 Wm^{-2}, while on a regular winter day, irradiation is below 200 Wm^{-2} with a short daylight period of 7.5 h on the shortest day (Breuer and Van de Braak, 1989). Therefore, Dutch type greenhouse structures were designed with a roof angle of 26° to intercept as much light as possible between autumn and spring as the daily light integral (DLI) for photosynthetically active radiation (PAR, mol m^{-2}) outside the greenhouse varies between 1.6 mol m^{-2} in some winter days to 75 mol m^{-2} in summer (Vanthoor, 2011). In the Westland, cooling is unnecessary, but heating and supplementary lighting are necessary for efficient year-round production (Bot, 2001; Buwalda et al., 1999; Kempkes and Van de Braak, 2000).

3.2. Climate data

Climate data has been sourced at the European Network for Earth System Modelling (ENES, 2020) accessed through the Copernicus Data Store (Copernicus Climate Change Service and Climate Data Store, 2021) for all four locations and the climate-change scenarios based on the *Representative Concentration Pathways* (RCPs) (van Vuuren et al., 2011), which represent different greenhouse-gas concentration trajectories. These pathways comprise CO_2 levels of 421 ppm (RCP2.6), 538 ppm (RCP4.5), and 936 ppm (RCP8.5) by the year 2100. As a starting point, we used hourly outside climate data for the Earth's surface (2m above ground) with global solar radiation, temperature, relative humidity and wind speed/direction for the four locations (METEO; www.meteoblue.com) for the year 2019. For the climate projections, we assessed the ENES-portal. We used the CMIP5 data set that provided daily average measures of the three RCP scenarios for the four locations and the climate-change scenarios for 2020–2029, 2040–2049 and 2090–2099 with e.g. temperature 2m above ground data-set MPI-ESM LR (**German Climate Computing Center; *Deutsches Klimarechenzentrum*, DKRZ**). The primary reference for the CMIP5 experiment design is described in (Taylor et al., 2012). Due to the need for hourly data to do precise greenhouse simulations, we have created hourly data-sets based on the information from METEO and IPCC; the differences of daily average METEO and the climate-change scenarios (in total nine for each location) were calculated and upscaled to hourly values.

3.3. Greenhouse and crop model

Data were analyzed within a commercially-tested greenhouse climate and control simulator to simulate specific climate, microclimate, and energy consumption (Körner and Hansen, 2012; Körner and Holst, 2017). Data applications were conducted as described in Goddek and Körner (2019). Influx energy to the greenhouse was based on global solar radiation outside the greenhouse, extrapolated to inside greenhouse indirect and diffuse short-wave radiation with a detailed wave-length distribution between 380 nm and 750 nm. The light input to the greenhouse was used to generate energy balances for macro- and microclimate, and photosynthesis. Direct transmission of the greenhouse cover was calculated as a function of azimuth and elevation of the sun specific for each location, with the diffuse transmission set to constant as a function of the cover material. Absorbed short-wave light energy by the crop was calculated from the short-wave gains and long-wave radiation losses. In addition to the trapped solar energy, which comprised the primary energy input to the greenhouse, the internal greenhouse energy budget in the simulator is calculated from inputs through heating systems and conductive and convective heat exchange processes inside the greenhouse and at the greenhouse shelter (i.e. the amount of pipe heating energy input to the greenhouse was determined through convective and radiative heat transfer), while energy losses were either through passive ventilation openings calculated from wind speed, vent opening and other openings as determining factors. Air-influx was also through the installed 'pad & fan' cooling systems for warm and dry locations (i.e. not in The Netherlands).

The latent heat balance (i.e. humidity) in the greenhouse environment was calculated from inputs from crop evapotranspiration (Körner et al., 2007), the 'pad & fan' cooling system, and air exchange between inside and outside the greenhouse, and condensation sinks on surfaces. Latent heat production by crop transpiration was calculated from crop microclimate as described in Körner et al. (2007), where the leaf energy balance was modelled based on leaf physical processes. Latent heat energy losses were calculated either by direct mass transfer to the outside air or by phase changes through condensation on the glass wall and the resulting convection losses that are influenced by the temperature of the greenhouse cover, outside air temperature, and wind speed. From that, relative humidity in the greenhouse air was determined. Climate control was done with heating and ventilation and implemented with a set of simple replicas of commercially available climate controllers.

Crop growth and yield were simulated with a photosynthesis-driven growth model for tomatoes based on an extensive collection of literature and data from the Wageningen school. The biochemical based FvCB leaf photosynthesis model (Farquhar et al., 1980) was used as a basis, while crop-specific variables for tomatoes were applied. Physical leaf resistances of stomata and leaf boundary layer were simulated as described in Janka et al. (2016). Photosynthetic capacity of leaves based on proximal locations within the plant was calculated and then upscaled to calculate total photosynthetic capacity and growth rates using a mathematical procedure integrating different levels of a crop canopy (i.e. 3-point Gaussian integration). Our model approach uses the sink-source strength method. First, crop dry weight is simulated from crop gross photosynthesis, maintenance respiration, and conversion efficiency. Then the dry weight is allocated to the separate plant organs as leaves, stems and generative organs through an interaction between source and sinks. This allocation is controlled by temperature and is crop-specific. Leaf area of the crop, usually denoted as an index of leaf coverage per area ground (leaf area index) was calculated from dry-matter allocation to the leaves and the seasonal and crop developmental stage-dependent adjustment factors. For our simulations, the tomato crop (cv. 'Pannovy') was maintained at a maximum lead area index of 3.5 (i.e. older leaves were removed weekly). The model calculates tissue dry weight as photo-assimilated carbohydrates while a constant dry weight content of harvested fruits of 5.0% was used.

3.4. Greenhouse design and equipment

For direct comparison between the locations and future scenarios, we have created a basic theoretical greenhouse structure with equipment that is suitable for all climate zones. The design is based on resource conservation, climatic influences and market factors (cf. Fig. 2). For handling the different regional and future climates, the greenhouse was equipped with climate controllers and actuators for passive and active

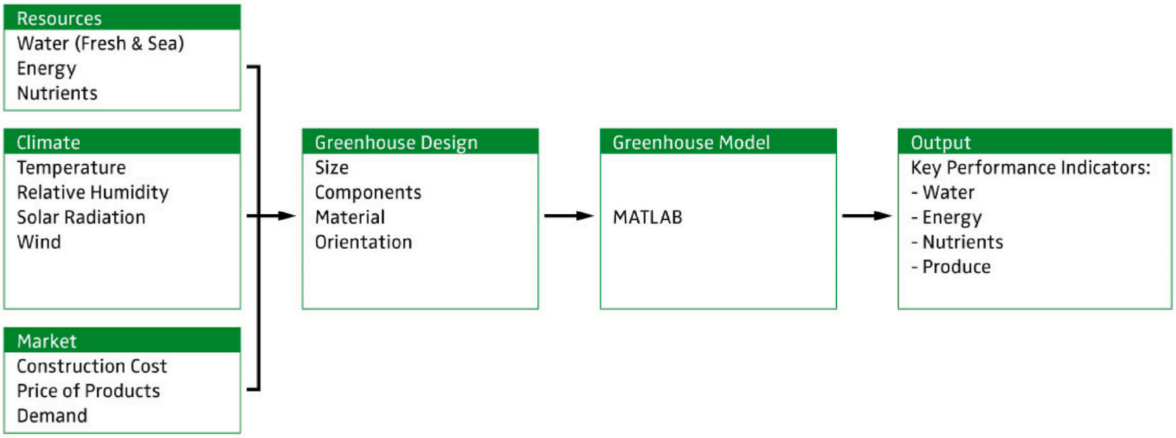

Fig. 2. Critical parameters of our modelling approach.

ventilation with cooling and pipe heating. At the same time, the capacities were adjusted to the specific needs of the model-based climate controller. As a general shelter model, a standard Dutch-type multi-span greenhouse was used for all cases based on the Dutch norm NEN 3859:2012 with single-glass (2m × 1m; U_w 7.5 Wm^{-2} K^{-1}; diffuse light transmission 92%; haze 30%) cover and other standard elements typically used for new construction as of 2019. The shelter had a roof slope of 26°, 9.6m span widths with two bays and 7.5m gutter heights. We constructed the virtual greenhouse as a semi-closed positive pressure 5ha (round truss tomato, 'Pannovy F1') monoculture cultivated in ten computer-controlled climate zones. Double layer inside greenhouse roof and sidewall screens were used with shading (diffuse light transmission 40%) and energy-saving (diffuse light transmission 30%) properties. For greenhouse cooling 'pad & fan' cooling systems either for freshwater (paper-based pads) or for brackish and saltwater (polyethylene-based pads) were used and modelled with physical processes using system parameters as, for example, pad thickness and material properties, ventilator speed and pressure as variable input parameters.

3.5. Model implementation, simulation scenarios and settings

The models (i.e. greenhouse climate and control and microclimate) were programmed in the simulation software environment MATLAB (MathWorks Inc., USA). The output of the simulations included biological and physical variables related to greenhouse production. However, for a structural overview, categories for key performance indicators were used (Fig. 2). At the same time, separate modules were compiled into one program input to the simulation program included, among others, physical location, relative humidity set point, setpoints for heating and ventilation, crop type, crop planting and replacement and termination dates. Based on these inputs, integrated modules and databases within the greenhouse simulator could be incorporated into simulation studies. For dynamic simulations, a weather database with hourly outside climate variables as specified under Section 3.2 specific for each location was utilized. The simulator calculated greenhouse climate in a time-step of 5 min and integrated controls (e.g. actuators for heating, ventilation, cooling and CO_2) that were re-adjusted as per standard climate controllers in commercial practice. Calculations were performed for all scenarios for single years (8760 h) of each of the 10-year horizons as described above. Means and standard deviation of the ten years simulation results were calculated for one-year periods.

4. Results

The objective of this paper was to determine the response capacity of desert greenhouse systems for the different climate-change scenarios and to explore the potential of industrial-scale greenhouse horticulture in arid regions near population centres concerning the above-mentioned performance indicators of water and energy under climate change using a numerical modular simulation model. Addressing geographic vulnerability to climate change is essential when coping with food security and water scarcity. The model outputs are presented in Figs. 3 and 4 and Tables 2 and 3. Fig. 3 illustrates the daily mean ambient temperature of the three climate-change model scenarios and the four modelled locations, whereas Fig. 4 shows the daily mean of greenhouse temperature for the four locations. Tables 2 and 3 provide the model data output of key performance indicators for the four countries' fresh crop weight, water consumption, and energy consumption.

5. Discussion

5.1. Climate change impact

The IPCC's future climate-change scenarios are based on assumptions on how future human emissions will develop and plausible emission pathways are entered into models to determine the consequent future climate. However, the Covid plandemic has shown that model forecasts should always be taken with a grain of salt (Ioannidis et al., 2020). Nevertheless, they can assist us in assessing potential threats and impacts. The results presented in Fig. 3 show that especially RCP8.5 is associated with a substantial rise in average temperature. This impression is reinforced in Table 2, which shows that the claimed temperature rise in the year 2100 can be from 3.2 °C in the Netherlands up to 6.0 °C in Namibia. The ecological and economic damage resulting from such substantial increases in temperature are challenging to assess (Schlenker and Auffhammer, 2018). However, if these climate change effects materialize as anticipated, combined with increased frequency of extreme weather conditions, they could pose a serious threat to agricultural production (Sivakumar et al., 2005; Vogel et al., 2019). One solution to counteract high ambient temperatures is to create an artificial environment in a greenhouse where climatic conditions can be regulated and yet allow light transmission. As mentioned in our hypothesis, the disadvantage of operating such greenhouses in temperate regions is that either water or electricity are required to achieve a climate equilibrium that guarantees optimal plant growth for cost-effectiveness. Therefore, water cooling systems are implemented in our simulator, and these lead to moderate indoor temperatures and reduced day-night temperature fluctuations (Fig. 4). As plants grow and flourish solely from light (i.e. photosynthesis), the excellent solar radiation intensity constitutes an advantage for growing crops in greenhouses in arid areas. However, stronger solar radiation is also correlated with higher ambient temperatures, inhibiting plant growth. Due to the (semi-)closed nature of greenhouse systems, they allow for the adaptation of environmental parameters.

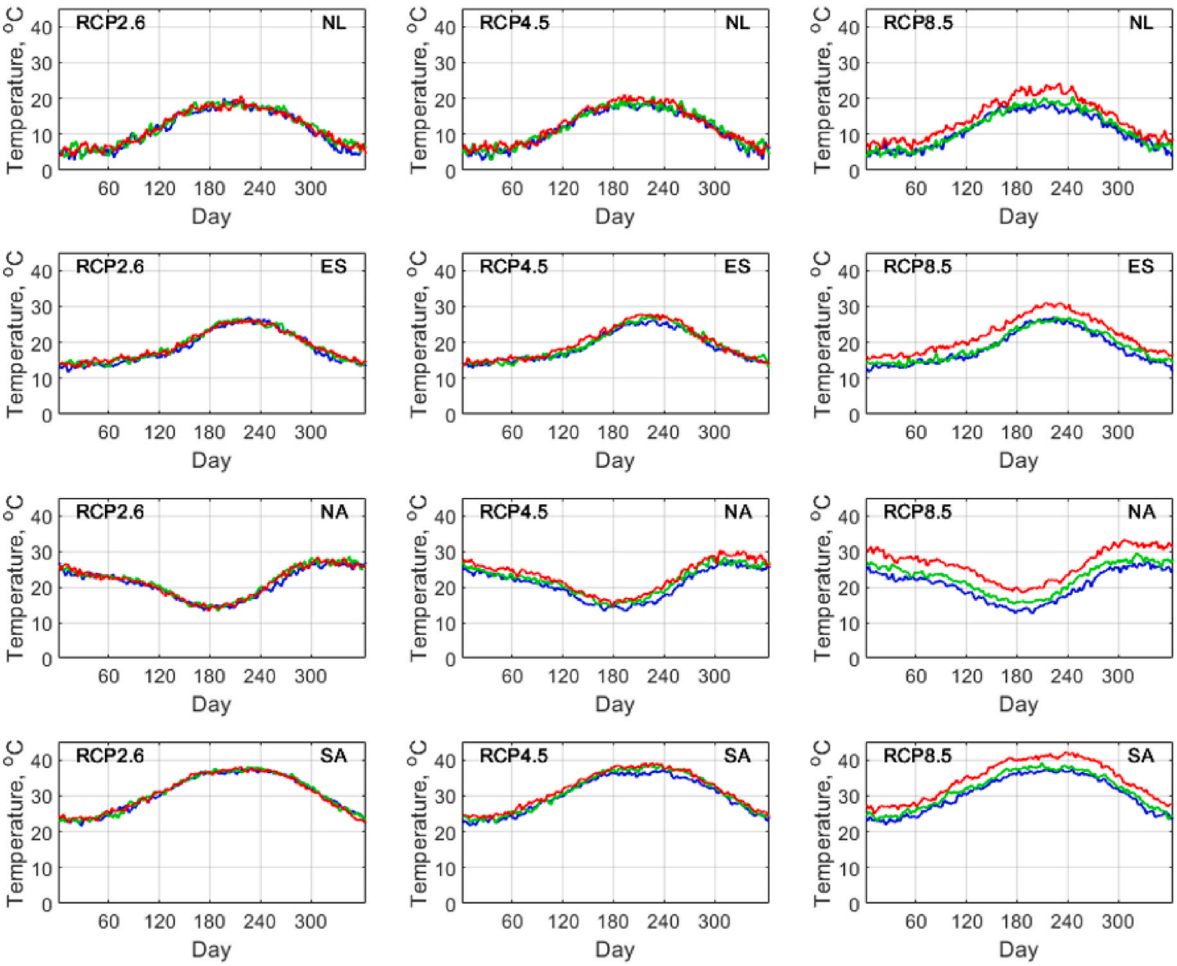

Fig. 3. The daily mean of outside temperature for the four locations (NL = Netherlands, ES = Spain, NA = Namibia, SA = Saudi Arabia) with three climate model scenarios in 2020–2029 (blue), 2040–2049 (green) and 2090–2099 (red) with a maximum air-flow requirement for cooling of 0.35 m^{-3} m^{-2} s^{-1}. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.).

Counteracting these high ambient temperatures inevitably leads to higher water consumption for cooling purposes, as seen in the 'saltwater consumption' column in Table 2. To reduce the freshwater footprint of future greenhouses, we decided to equip our virtual greenhouse with a 'pad & fan' cooling system that can deal with high degrees of salinity (see Section 4.3). Interestingly, the differences in required water quantity between the status quo and the worst-case scenario in 2100 are manageable. 6.9% more freshwater would be required per kilo of tomatoes in the Netherlands (no cooling system applied). Spain (+16.4%), Namibia (+17.9%), and Saudi-Arabia (+13.3%) require more water per kg of fresh weight yield. However, these countries need to compensate for the higher external temperatures, mostly at the expense of saltwater consumption. Also, the yield quantity decreases by 3%–6% due to slightly deteriorating growth conditions within the greenhouse (Fig. 4).

A fundamental matter for debate is the energy use efficiency (Table 3). Thermal energy demand is associated with the need to heat the greenhouse during the night, whereas electrical energy demand depends on the required cooling requirements (i.e. fan speed). Contrary to Spain, Namibia, and Saudi Arabia, the energy use efficiency increases by a quart in the Netherlands as an increase in ambient temperatures would decrease the thermal energy demand. In contrast to the Netherlands, the other three locations require a higher total energy demand per yield unit. Having drawn a bleak picture, we can fairly say that generating electrical energy in Spain, Namibia, and Saudi Arabia will not present a significant problem considering their enormously high solar irradiation levels ideal for solar energy.

Another vital concern is local food security. Having locally-produced fresh food with a relatively short shelf-life improves the food-miles for transport, including maintaining the cold chain (Passel, 2013) (and reduces transportation-related greenhouse-gas emissions). Also, shortening delivery channels reduces the 'farm-to-fork' time, leading to more nutritious products reaching the consumers (Rickman et al., 2007). From a production-wise point of view, pest management is crucial within horticultural systems. Fewer pesticides would be required due to the arid climate.

5.2. Desalination and brine disposal

Even though desalination technology provides an opportunity to produce freshwater for greenhouse use, the brine, a by-product of the desalination process, is potentially toxic (Giwa et al., 2017). Brine management and disposal strategies are thus necessary and must be in line with local laws and regulations (Panagopoulos et al., 2019). Given that desert areas usually do not allow for surface water discharge, costly evaporation ponds often are the only option to treat brine. Disposal through the use of salt roads (a mixture of saltwater and gypsum) might be possible if road construction is needed. From an economic viewpoint, the evaporation ponds could potentially grow brine shrimp (e.g. Artemia salina) or recover resources to generate additional value (Zmora and Shpigel, 2006). Brine can also be used for cooling the greenhouse (see Section 5.3).

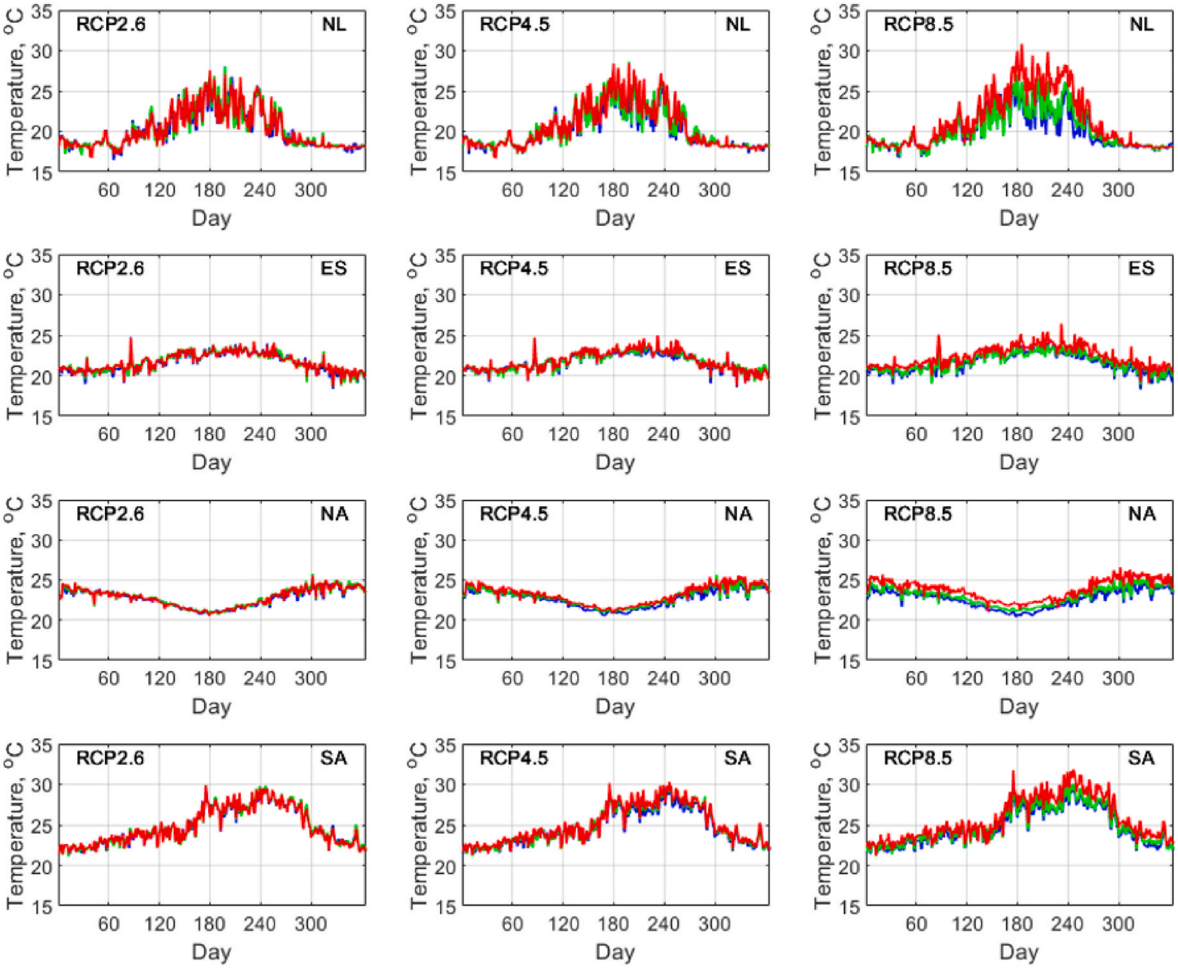

Fig. 4. The daily mean of greenhouse temperature for the four locations (NL = Netherlands, ES = Spain, NA = Namibia, SA = Saudi Arabia) with three climate model scenarios in 2020–2029 (blue), 2040–2049 (green), and 2090–2099 (red) with a maximum air-flow requirement for cooling of 0.07 m^{-3} m^{-2} s^{-1} in ES, NA, and SA. No cooling was applied in The Netherlands. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

5.3. Saltwater cooling system

Evaporative cooling is the most widely used method for maintaining appropriate greenhouse conditions in arid regions because of the low energy footprint and as it adds humidity to dry air. However, evaporative cooling consumes large amounts of water, often up to 90% of the total water use of desert greenhouses (Lefers et al., 2016). As shown in Table 2, the water consumption in Saudi Arabia is approximately three times higher than in the Netherlands, which highlights the need for saltwater cooling systems.

Although further development of saltwater-based evaporative cooling systems is essential to reduce fresh water consumption in arid regions, these cooling systems certainly offer a potential solution to this problem insomuch as these systems use brackish water, seawater or even brine for cooling as an alternative to precious freshwater. This is especially relevant for regions that would require energy-intensive desalinated water (Akinaga et al., 2018; Zamen et al., 2013). Access to saltwater resources in arid environments is possible in locations where seawater or brackish groundwater is available; many arid sites will have access to at least one of these sources (van Weert et al., 2009). Although saltwater evaporative cooling is promising, its commercial use is limited by concerns over precipitation of salts on evaporative pads, questions about what to do with the brine generated from this process, and concerns with salt aerosols that enter the greenhouse. However, recent technological advances have advanced saltwater evaporative cooling, and it now can contribute considerably to reduced water use and greater energy efficiencies in desert greenhouses (Lefers et al., 2018). Since electrical energy production is much cheaper in most hot and arid areas, the increased need for cooling (i.e. higher required ventilation capacity) should be economically negligible.

5.4. SDG contribution and resilience

Contributing to the sustainable development goals (SDGs) is associated with building resilience by some scholars (Folke et al., 2002; Roberts et al., 2015). For example, greenhouses horticulture in arid regions or unfertile land contributes to the SDGs (see Fig. 5) by making it possible to grow food regardless of the soil quality and ambient climate (SGD2: zero hunger); providing nutritious local and fresh food (SGD3: good health and well-being); providing a climate-resilient technology (SGD9: industry, innovation, and infrastructure); producing food with a high degree of water and nutrient use efficiencies (SGD12: responsible consumption and production); and coming up with a potential mitigation and adaption strategy to ‘reduce climate change’ (SGD13: climate action).

In particular, using fallow land to grow food on an industrial scale might help decrease the necessity of deforestation and slash and burn to guarantee global food safety. The higher the functionality of ecosystems, the higher their resilience during extreme weather conditions. However, policies are required to secure the participation of smallholder farmers

Table 2
The model data output of the key performance indicators crop fresh weight and water consumption for the four countries (NL = The Netherlands; ES = Spain; NA = Namibia; SA = Saudi Arabia) with the three climate model scenarios.

Country	Climate Scenario	Year	Mean Ambient Temperature	Δ Temp.	Tomato Fresh Weight	Fresh Water Consumption	Salt Water Consumption	Total Water Consumption	Water Use Efficiency
			°C	K	kg m^{-2}	m3 m^{-2}	m3 m^{-2}	m3 m^{-2}	kg m^{-3}
NL	RCP 26	2020–9	11.35 ± 0.83	0.00	73.27 ± 0.89	1.37 ± 0.01	0.00 ± 0.00	1.37 ± 0.01	53.36 ± 0.90
		2040–9	11.93 ± 0.76	0.58	72.86 ± 0.98	1.37 ± 0.01	0.00 ± 0.00	1.37 ± 0.01	53.07 ± 1.06
		2090–9	11.90 ± 0.43	0.55	72.99 ± 0.50	1.37 ± 0.01	0.00 ± 0.00	1.37 ± 0.01	53.19 ± 0.64
	RCP 45	2020–9	11.46 ± 0.49	0.00	73.26 ± 0.87	1.37 ± 0.01	0.00 ± 0.00	1.37 ± 0.01	53.32 ± 0.96
		2040–9	12.07 ± 0.57	0.61	72.71 ± 0.73	1.38 ± 0.01	0.00 ± 0.00	1.38 ± 0.01	52.75 ± 0.76
		2090–9	12.46 ± 0.43	1.00	72.08 ± 0.79	1.38 ± 0.01	0.00 ± 0.00	1.38 ± 0.01	52.17 ± 0.80
	RCP 85	2020–9	11.19 ± 0.42	0.00	73.73 ± 0.54	1.37 ± 0.01	0.00 ± 0.00	1.37 ± 0.01	53.91 ± 0.58
		2040–9	11.80 ± 0.51	0.61	72.90 ± 0.41	1.38 ± 0.01	0.00 ± 0.00	1.38 ± 0.01	52.99 ± 0.56
		2090–9	14.40 ± 0.68	3.21	69.54 ± 1.49	1.40 ± 0.01	0.00 ± 0.00	1.40 ± 0.01	49.70 ± 1.50
ES	RCP 26	2020–9	18.58 ± 0.63	0.00	71.86 ± 0.89	1.39 ± 0.00	0.88 ± 0.06	2.27 ± 0.06	31.71 ± 1.18
		2040–9	19.04 ± 0.59	0.46	71.60 ± 0.69	1.39 ± 0.01	0.91 ± 0.06	2.30 ± 0.05	31.12 ± 1.00
		2090–9	19.12 ± 0.47	0.54	71.47 ± 0.92	1.39 ± 0.01	0.92 ± 0.05	2.31 ± 0.04	30.93 ± 0.93
	RCP 45	2020–9	18.81 ± 0.55	0.00	71.83 ± 0.73	1.39 ± 0.00	0.89 ± 0.05	2.28 ± 0.04	31.48 ± 0.91
		2040–9	19.28 ± 0.29	0.47	71.35 ± 0.78	1.39 ± 0.01	0.94 ± 0.03	2.33 ± 0.03	30.65 ± 0.67
		2090–9	19.80 ± 0.51	0.99	70.73 ± 0.89	1.38 ± 0.01	0.98 ± 0.05	2.37 ± 0.04	29.90 ± 0.89
	RCP 85	2020–9	18.47 ± 0.30	0.00	71.84 ± 0.40	1.39 ± 0.01	0.87 ± 0.03	2.26 ± 0.03	31.77 ± 0.48
		2040–9	19.19 ± 0.39	0.72	71.37 ± 0.54	1.39 ± 0.01	0.94 ± 0.04	2.32 ± 0.03	30.75 ± 0.62
		2090–9	22.01 ± 0.27	3.54	68.32 ± 0.43	1.38 ± 0.01	1.20 ± 0.03	2.58 ± 0.03	26.50 ± 0.45
NA	RCP 26	2020–9	20.92 ± 0.87	0.00	73.50 ± 1.00	1.99 ± 0.02	1.05 ± 0.06	3.04 ± 0.07	24.22 ± 0.87
		2040–9	21.54 ± 0.58	0.62	72.73 ± 0.93	2.00 ± 0.01	1.10 ± 0.04	3.09 ± 0.05	23.53 ± 0.64
		2090–9	21.39 ± 0.43	0.48	73.32 ± 0.48	1.99 ± 0.01	1.09 ± 0.03	3.08 ± 0.04	23.80 ± 0.43
	RCP 45	2020–9	20.64 ± 0.66	0.00	74.12 ± 0.73	1.98 ± 0.02	1.03 ± 0.04	3.02 ± 0.05	24.59 ± 0.47
		2040–9	21.77 ± 0.87	1.13	72.82 ± 0.89	2.00 ± 0.01	1.11 ± 0.06	3.11 ± 0.07	23.42 ± 0.81
		2090–9	23.02 ± 0.99	2.38	71.72 ± 0.76	2.01 ± 0.01	1.20 ± 0.07	3.21 ± 0.08	22.36 ± 0.77
	RCP 85	2020–9	20.40 ± 1.15	0.00	74.10 ± 1.40	1.98 ± 0.01	1.02 ± 0.08	3.00 ± 0.10	24.76 ± 1.21
		2040–9	22.51 ± 0.96	2.11	72.27 ± 1.13	2.01 ± 0.02	1.16 ± 0.07	3.17 ± 0.08	22.81 ± 0.91
		2090–9	26.36 ± 1.01	5.97	69.23 ± 0.96	2.02 ± 0.01	1.47 ± 0.08	3.49 ± 0.08	19.88 ± 0.68
SA	RCP 26	2020–9	30.60 ± 0.46	0.00	76.42 ± 0.39	1.49 ± 0.01	2.10 ± 0.05	3.59 ± 0.05	21.27 ± 0.35
		2040–9	30.81 ± 0.36	0.21	76.39 ± 0.28	1.50 ± 0.01	2.12 ± 0.04	3.62 ± 0.04	21.12 ± 0.24
		2090–9	30.74 ± 0.32	0.14	76.67 ± 0.50	1.49 ± 0.00	2.11 ± 0.03	3.61 ± 0.04	21.27 ± 0.30
	RCP 45	2020–9	30.22 ± 0.33	0.00	76.86 ± 0.36	1.49 ± 0.01	2.06 ± 0.03	3.55 ± 0.04	21.66 ± 0.31
		2040–9	31.03 ± 0.32	0.81	76.30 ± 0.53	1.50 ± 0.01	2.14 ± 0.03	3.64 ± 0.03	20.95 ± 0.32
		2090–9	31.69 ± 0.49	1.47	75.99 ± 0.50	1.50 ± 0.00	2.22 ± 0.05	3.71 ± 0.05	20.47 ± 0.39
	RCP 85	2020–9	30.43 ± 0.33	0.00	76.67 ± 0.50	1.49 ± 0.01	2.08 ± 0.04	3.57 ± 0.04	21.45 ± 0.29
		2040–9	31.63 ± 0.32	1.20	75.88 ± 0.48	1.49 ± 0.01	2.21 ± 0.03	3.70 ± 0.04	20.51 ± 0.27
		2090–9	34.37 ± 0.63	3.94	74.32 ± 0.54	1.52 ± 0.01	2.51 ± 0.07	4.03 ± 0.08	18.44 ± 0.45

Table 3

The model data output of the key performance indicator energy consumption for the four countries (NL = The Netherlands; ES = Spain; NA = Namibia; SA = Saudi Arabia) with the three climate model scenarios.

Country	Climate Scenario	Year	Thermal Energy Demand			Electrical Energy Demand			Total Energy Demand			Energy Use Efficiency		
			MJ m-2			MJ m-2			MJ m-2			kg KJ-1		
NL	RCP 26	2020–9	1138.77	±	92.80	0.00	±	0.00	1138.77	±	92.80	11349.63	±	832.55
		2040–9	1053.59	±	100.52	0.00	±	0.00	1053.59	±	100.52	11932.56	±	755.92
		2090–9	1067.52	±	65.36	0.00	±	0.00	1067.52	±	65.36	11903.31	±	425.35
	RCP 45	2020–9	1125.17	±	59.47	0.00	±	0.00	1125.17	±	59.47	11463.35	±	494.03
		2040–9	1049.77	±	87.08	0.00	±	0.00	1049.77	±	87.08	12073.66	±	565.56
		2090–9	1021.07	±	67.03	0.00	±	0.00	1021.07	±	67.03	12464.80	±	425.23
	RCP 85	2020–9	1158.00	±	55.30	0.00	±	0.00	1158.00	±	55.30	11191.08	±	418.42
		2040–9	1089.32	±	92.45	0.00	±	0.00	1089.32	±	92.45	11803.16	±	514.28
		2090–9	805.25	±	57.80	0.00	±	0.00	805.25	±	57.80	14396.33	±	681.84
ES	RCP 26	2020–9	192.18	±	5.49	951.23	±	57.10	1143.41	±	58.29	18578.08	±	632.91
		2040–9	191.89	±	4.12	991.10	±	58.17	1182.99	±	59.55	19041.20	±	592.30
		2090–9	190.87	±	3.53	1002.67	±	44.24	1193.54	±	44.05	19121.54	±	465.18
	RCP 45	2020–9	189.61	±	6.45	971.04	±	46.41	1160.65	±	45.52	18811.29	±	554.77
		2040–9	186.21	±	6.98	1012.98	±	29.73	1199.19	±	35.17	19283.26	±	287.22
		2090–9	189.39	±	4.30	1054.68	±	42.50	1244.07	±	40.22	19804.76	±	514.76
	RCP 85	2020–9	197.19	±	5.71	949.27	±	31.54	1146.46	±	32.47	18469.84	±	299.02
		2040–9	192.18	±	3.23	1014.07	±	35.85	1206.26	±	37.31	19193.76	±	391.24
		2090–9	181.85	±	4.73	1232.44	±	20.40	1414.28	±	22.74	22014.53	±	270.66
NA	RCP 26	2020–9	155.77	±	4.69	1176.60	±	57.77	1332.37	±	56.51	20915.76	±	867.32
		2040–9	158.37	±	1.30	1221.60	±	41.56	1379.96	±	41.41	21535.27	±	581.57
		2090–9	158.68	±	3.50	1214.82	±	35.17	1373.50	±	38.14	21394.40	±	431.06
	RCP 45	2020–9	157.22	±	4.53	1159.81	±	42.57	1317.04	±	41.59	20637.01	±	655.31
		2040–9	154.91	±	1.60	1233.92	±	59.36	1388.84	±	59.30	21770.76	±	870.76
		2090–9	160.65	±	2.94	1328.23	±	69.23	1488.88	±	70.70	23020.39	±	986.13
	RCP 85	2020–9	157.95	±	5.24	1142.18	±	86.82	1300.13	±	90.59	20399.02	±	1147.61
		2040–9	159.33	±	3.80	1290.47	±	68.36	1449.79	±	68.80	22512.60	±	961.48
		2090–9	172.58	±	5.77	1576.14	±	81.73	1748.72	±	87.13	26364.13	±	1010.33
SA	RCP 26	2020–9	171.01	±	3.58	2101.58	±	41.74	2272.59	±	44.42	30598.96	±	458.51
		2040–9	171.39	±	4.12	2122.45	±	30.79	2293.83	±	33.99	30807.98	±	358.70
		2090–9	172.15	±	2.83	2113.08	±	34.22	2285.23	±	36.00	30741.70	±	316.11
	RCP 45	2020–9	169.79	±	3.23	2055.59	±	40.35	2225.38	±	40.70	30215.59	±	325.15
		2040–9	171.62	±	3.49	2146.70	±	32.26	2318.32	±	34.15	31026.20	±	320.69
		2090–9	175.20	±	3.32	2199.23	±	45.33	2374.43	±	47.79	31687.00	±	491.68
	RCP 85	2020–9	171.29	±	3.50	2083.83	±	36.05	2255.12	±	37.34	30433.25	±	333.33
		2040–9	176.56	±	2.57	2200.09	±	32.56	2376.65	±	34.22	31631.22	±	316.77
		2090–9	181.73	±	2.71	2450.91	±	55.36	2632.64	±	57.22	34371.48	±	631.36

Fig. 5. Contribution of greenhouse horticulture in arid regions to the Sustainable Development Goals.

who are also responsible for land-use changes such as the clearing of forests.

Another climate-resilient aspect that should be highlighted s that the relative loss of productivity (3–6%) in semi-arid greenhouse systems in the most extreme climate scenarios is much lower than for more conventional farming practices in these regions will probably become impossible. The efficiency losses are manageable (i.e. water use efficiency minus 13–18%; energy use efficiency minus 16–28%). However, more integrated economic feasibility studies are essential to combine all aspects of these greenhouse systems to better illustrate the enormous economic potentials of such systems if these scenarios become reality.

6. Conclusions

Controlled environmental conditions within greenhouses prevent a significant reduction in harvest predictions. Thus, desert-greenhouse farming principally has a high potential for enhancing regional, national and global food security (tomato fresh weight >70 kg/m^2; Table 2) and such farming systems should be an integral part of climate-change mitigation and adaptation strategies. The outstanding light level in most arid regions is the main steering factor for plant growth. Despite the expected increasing needs of energy (i.e. decreasing energy use efficiency by 19%–39%; Table 3) and total water requirement per yield unit (13%–18%; Table 2) in arid areas, the elaborated scenarios show a high degree of climate resilience, and this makes growing fresh vegetables in arid and infertile regions now and in the future possible. In conclusion, it is ultimately important to emphasize that the IPCC models are theoretical in nature, and we cannot be certain whether and to what extent they will materialize as claimed.

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

We used public IPCC data as model simulation input provided by the European Network for Earth System Modelling (ENES, 2020) and accessed through the Copernicus Data Store (Copernicus Climate Change Service and Climate Data Store, 2021). The greenhouse simulator used was published and described in earlier work.

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