Femeena and Brennan
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Lemnaceae as a resilient crop to improve food security under climate extremes: global warming and post-catastrophic cooling scenarios

P. V. Femeena[1] and R. A. Brennan[1*]

Abstract

Background Future impacts of rising temperatures and extreme weather events on agriculture are expected to be severe, potentially resulting in a 25% reduction in global crop yields by 2050. As a risk multiplier, global warming also exacerbates existing conflicts over natural resources. In the event of large-scale conflicts like nuclear war, food production could suffer significantly, potentially declining by 90% in global average calorie production due to the resulting cold and dark weather conditions. *Lemnaceae* (commonly known as 'duckweed') is a family of prolific aquatic plants and a high-protein food source. It is capable of growing in extreme hot or cold conditions, where conventional crops struggle. This study investigates the effects of both global warming and post-nuclear war cooling on duckweed growing seasons and biomass production. A plant growth model was coupled with climate data to predict annual duckweed yields across 20 locations worldwide, considering two global warming scenarios: (1) an optimistic sustainable pathway with low greenhouse gas emissions and (2) a fossil fuel-dominated pathway with medium to high greenhouse gas emissions. We also examined three post-nuclear war cases with different atmospheric carbon injections.

Results In low-latitude equatorial regions, global warming and the low-emission nuclear war case had minimal impact on duckweed yields (less than 6% change from baseline), whereas higher latitudes experienced yield increases (up to 90%) with global warming. The high-emission nuclear war cases showed a significant reduction in yields, but equatorial regions could still produce 19–20 metric ton/ha of duckweed annually.

Conclusions The findings from this work substantiate the versatility of duckweed to improve global food security under both global warming and post-catastrophic cooling scenarios.

Keywords Duckweed, Climate change, Nuclear war, Food security, Whole protein, Climate resilience

Introduction

Over 30% of the world's population currently faces moderate or severe food insecurity [19]. Fueled by various physical and socio-economic factors, access to food is declining at an alarming rate. According to a recent report by the Food and Agriculture Organization (FAO) and the World Food Programme (WFP), up to 205 million people in 45 countries were expected to face severe food insecurity and to be in need of urgent assistance

*Correspondence:
R. A. Brennan
rab44@psu.edu
[1] Department of Civil and Environmental Engineering, The Pennsylvania State University, 208 ECoRE Building, 556 White Course Drive, University Park, PA 16802, USA

during the period from October 2022 to January 2023, causing hunger hotspots in almost 19 countries [68].

Climate change is already a major contributor to global food system instability, with extreme weather events such as droughts, floods, and heatwaves reducing agricultural productivity and threatening food availability. Natural disasters accounted for 63% of the farming losses between 2008 and 2018 in low- and middle-income countries [18]. It is expected that in the upcoming decades, there will be a rise in the duration, frequency, intensity, and spatial scope of extreme weather conditions. For example, individuals born in 2020 are likely to encounter two to seven times more extreme weather events than those born in 1960 [65].

Beyond gradual climate change, abrupt and extreme disruptions could have even more severe consequences for food production. These include events such as super volcanic eruptions or a nuclear war which are expected to result in abrupt climatic changes following the disaster [74]. Episodes like these would lead to unusual atmospheric cooling (due to sulfuric acid aerosols from volcanic eruptions or soot injection from nuclear wars), affecting crop yields and growing seasons for many subsequent years. Past examples include the famines caused by volcanic cooling following the 1781 Laki eruption in Iceland and the 1815 Tambora eruption in Indonesia [48, 72]. Similar atmospheric cooling would occur following a nuclear war. Simulation models have projected that more than 5 billion people would die of hunger following a full-scale nuclear war between the United States and Russia, with temperatures going well below the freezing point in the northern hemisphere [15, 74]. Even a small-scale nuclear conflict between India and Pakistan is estimated to put 2.3 billion people at risk of starvation or severe food insecurity [28]. While the mechanisms of climate change and nuclear winter differ—one leading to warming, the other to cooling—both pose significant threats to agricultural productivity, emphasizing the need for resilient food sources that can withstand a wide range of environmental stresses.

Given the global risks posed by extreme climate fluctuations, it is essential to develop strategies that enhance food security and disaster preparedness across different geographic regions. Both climate change and catastrophic events like nuclear war have temporally and spatially varying effects on crop yields. The geographically varying impacts of global warming on crop yields are well documented; for example, tropical regions are expected to be more vulnerable to climate change and could lose up to 200 growing degree days (GDD) annually by 2100 [14]. GDD is a measure of heat accumulation over a plant's growing season and is used to calculate the growth stage of crops. Although the immediate and most detrimental effects of a nuclear war would be felt in regions surrounding the source of the soot injection in the years immediately following the war, far-reaching impacts on food availability would be felt at a much larger, global scale. Hence, it is critical to study food resilience from a global perspective and identify the similarities or differences in how climatic perturbations for both warming and cooling are likely to affect spatial patterns of crop productivity.

Historically, efforts to address food security in the face of climate change have focused on developing crops that can withstand extreme weather conditions. Recent advances in genetic engineering and molecular breeding approaches have resulted in crop varieties (e.g., transgenic rice) that are resilient to environmental stresses, such as droughts and floods [30, 33]. While the modified crop varieties help address the food security problem to a certain extent, these crops may still fail when exposed to extreme weather changes outside the predicted temperature/precipitation patterns from global warming climate models. For example, atmospheric cooling from an India–Pakistan nuclear war could result in irrecoverable damage to rice cultivation in mainland China [73]. Therefore, along with developing global warming-resistant crop varieties, it is increasingly important to find alternate crops that can grow under other extreme weather conditions to substitute or complement the dietary needs of those who may be affected by catastrophic emergencies. Given that global warming-induced disasters are becoming more frequent (fivefold increase in the last 50 years [69]) and that the threat of a nuclear war has been increasing at a disturbing rate over the past two decades [25], it would be prudent to integrate new crop(s) or cropping practice(s) into our existing agricultural system as quickly as possible. In addition to aiding a smooth transition into the changing climate, this would help maintain a sustainable food production system with reduced dependence on conventional crops, even before a disaster strikes.

One such potential crop is *Lemnaceae* (commonly known as 'duckweed'). It is a small aquatic plant popular for its robust and prolific nature. Although considered a water-weed, a vast array of research has been conducted on the many beneficial applications of duckweed. These include the utilization of its high protein content (up to 45%) in generating human food and animal feed [20, 57], as well as potentially using it as a bioenergy feedstock [9] and a bio-based fertilizer [22, 34]. Recently, duckweed is gaining popularity as an eco-friendly whole-protein superfood that can be used as a substitute for the protein derived from meat-based products [7, 76]. Besides its high doubling rate and harvesting ease, duckweed has promising value as a future-resilient crop due to its ability to tolerate a wide range of environmental conditions (temperatures of 5–33 °C and pH of 5.5–8.5) [10, 41]. It can even thrive under very low light intensities, making it a favorable crop species to grow under cold and dark weather scenarios, such as that following a nuclear war [21].

Crops such as quinoa, millet, and sorghum are also frequently highlighted for their resilience to drought and poor soil conditions. While these crops have proven to be valuable in certain regions, duckweed offers several distinct advantages in terms of: (1) increased productivity (with multiple harvests in a year); (2) less use of water; and (3) higher protein content. With a protein-yielding potential of five to ten times more than land-grown crops, such as soybean, duckweed could potentially be utilized to help meet daily human protein requirements [57]. In addition, while crops such as quinoa and millet rely on arable land and may face competition with staple crops, duckweed can be cultivated in non-arable areas, such as ponds or even wastewater systems, reducing competition for agricultural space. Although in its raw form duckweed is mostly viewed as a low-calorie food (frozen duckweed has 40 cal per 100 g), in dry powdered form it is considered a superfood and can provide up to 400 cal per 100 g, which is higher than other protein sources such as chicken and beef [23] (https://myfitnesspal.com). Unlike conventional crops, duckweed can also be farmed indoors in vertical farming settings without using much land area. This means that by developing a household duckweed cultivation system, one can have access to protein-rich food in emergencies when other food items, especially livestock products, are inaccessible. The duckweed research community has already demonstrated through several studies that duckweed exhibits elevated nutrient-uptake efficiency from wastewater [2, 13]. By growing duckweed on domestic or agricultural wastewater, we can parallelly achieve the dual functions of waste management and food production. Duckweed's multifunctionality to both recover nutrients from waste streams and produce high quality protein has applications both in existing or future business-as-usual scenarios, and perhaps more importantly, in the extreme circumstance of a disaster or catastrophic event.

To assess the ability of duckweed or any other crop to withstand changes in environmental conditions and to calculate their yield responses to future/hypothetical scenarios, models are crucial. Crop growth models are specifically used to predict changes in crop productivity under varied scenarios and environmental stressors. When used in conjunction with models that provide climate data for different futuristic scenarios, it can be a powerful tool for predicting yield responses to changes in weather variables, such as temperature and solar radiation [5, 31, 50]. Duckweed growth models, like the one developed by Lasfar et al. [40] and later enhanced by Femeena et al. [21], can be used in this manner to predict duckweed biomass yields under different climate scenarios, ranging from gradual climate change to an abrupt nuclear war [21].

The overall goal of this study is to assess the potential of duckweed as a climate-resilient food source by evaluating its growth under both future global warming and post-nuclear war cooling scenarios. Specifically, we aim to assess how varying levels of global warming and nuclear winter conditions would impact duckweed growth and yields in different geographic regions. We do this by evaluating geographical differences in duckweed yields under different climate scenarios and determining correlations between their GDD and yield. To the best of the authors' knowledge, this is the first time that duckweed growth models have been utilized to predict changes in yield under different scenarios generated from climate models. Although duckweed's tolerance to minor changes in the weather is already well-established, this modeling work is valuable in providing a scientific validation of duckweed's upper and lower weather thresholds. The outcomes of this study also enable us to predict if duckweed can survive and grow sufficiently under the most extreme weather conditions and to discover the optimal geographic locations, where duckweed should show the highest climate resilience.

Methodology

This study used a modified version of a duckweed growth model to simulate average annual duckweed yields under various climate scenarios in different locations around the world. The duckweed growth model and the climate data utilized for the different scenarios are described in detail in the following sections.

Duckweed growth model

We simulated duckweed growth using an enhanced model developed by Femeena et al. [21], as illustrated in Eqs. (1)–(3). This model is an improvement over an intrinsic duckweed growth model proposed by Lasfar et al. [40] that predicts the specific growth rate of duckweed based on mat density (duckweed biomass per area), temperature, photoperiod (length of the day), and nutrient concentrations in the growing media. The authors originally calibrated this model using data from laboratory experiments and further validated against literature data. Our enhancement to the model includes an additional term to incorporate the effect of light intensity on duckweed growth. The enhanced model has additionally been calibrated and validated against both our own experimental data and those from other duckweed growth studies [21]:

$$r_i = \left(R \cdot \theta_1^{\left((T-T_{\text{op}})/T_{\text{op}}\right)^2} \cdot \theta_2^{\left((T-T_{\text{op}})/T_{\text{op}}\right)} \cdot \theta_3^{\left((E-E_{\text{op}})/E_{\text{op}}\right)^2} \cdot \theta_4^{\left((E-E_{\text{op}})/E_{\text{op}}\right)} \cdot \frac{C_{\text{P}}}{C_{\text{P}}+K_{\text{P}}} \cdot \frac{K_{\text{IP}}}{K_{\text{IP}}+C_{\text{P}}} \cdot \frac{C_{\text{N}}}{C_{\text{N}}+K_{\text{N}}} \cdot \frac{K_{\text{IN}}}{K_{\text{IN}}+C_{\text{N}}} + A_0 \right) . A_1 . \left(\frac{\ln(LI) - A_2}{A_2} \right) \tag{1}$$

$$D = \frac{D_{\text{L}} \cdot D_{\text{O}}}{(D_{\text{L}} - D_{\text{O}}) \cdot e^{-r_i \cdot t} + D_{\text{O}}} \tag{2}$$

$$r_s = \frac{1}{t} \cdot \ln\left(\frac{D}{D_{\text{O}}}\right) = \frac{1}{t} \cdot \ln\left(\frac{D_{\text{L}}}{(D_{\text{L}} - D_{\text{O}}) \cdot e^{-r_i \cdot t} + D_{\text{O}}}\right) \tag{3}$$

where K_{P}, K_{IP}, K_{N}, and K_{IN} are the saturation and inhibition constants of phosphorus (P) and nitrogen (N) uptake, respectively; C_{P} and C_{N} are the P and N concentrations (mg L^{-1}) in the growing media, respectively; R is a constant (maximum intrinsic growth rate in day^{-1}); T is the temperature in °C with T_{op} being the optimum temperature for growth; E is the photoperiod or daylength (h); r_i and r_s are the intrinsic and specific growth rates (day^{-1}), respectively; LI is the light intensity (μmol m^{-2} s^{-1}); D_o is the initial density of the duckweed mat (g m^{-2}); D is the instant mat density (g m^{-2}) (i.e., the duckweed biomass per square meter of covered water surface at a specific moment in time); and D_L is the limiting mat density (g m^{-2}) (i.e., the upper limit of the mat density beyond which the duckweed growth is strongly inhibited); t is the duckweed retention time (day); and $\theta_{1\text{-}4}$ are nondimensional constants. $A_0=0.222$, $A_1=0.05$, and $A_2=0.681$ are the newly introduced constants by Femeena et al. [21].

Calicioglu et al. [11] used a similar model as described above to simulate large-scale duckweed cultivation and harvesting over an entire year (365 days). Parameter values that produced ideal duckweed yields in the Calicioglu et al. study (harvest threshold = 99 g/m^2, harvest ratio = 0.2, and harvest frequency = 1 day) were incorporated into our current model to predict optimal duckweed yields. These values specifically refer to the duckweed harvesting process, i.e., harvesting is only done when it meets the threshold density of 99 g/m^2, and only 20% of the duckweed mat is harvested every other day. The underlying assumption in this model is that duckweed is grown in aqueous media with fixed nutrient concentrations, with only light intensity and temperature as the changing variables corresponding to the simulated climate scenario.

The model, initially developed in Stella Architect (a dynamic systems modeling software) for the Calicioglu et al. [11] study, was converted to R programming language using a freely available package called 'StellaR' [46]. This was carried out to enable stand-alone simulations of the model with additional climate scenarios. An additional code modification was done to represent duckweed death at temperatures below 5 °C.

Grid selection

The environmental variables used in the duckweed growth model, precisely temperature (T) and light intensity (LI), vary both temporally (for different days of the year) and spatially (depending on the location where duckweed grows). To compare the spatial difference in duckweed yields, we examined multiple regions worldwide by generating equally spaced grids in latitudinal and longitudinal directions and selecting discrete locations located approximately in the center of each grid (Fig. 1). Twenty locations were selected using this method, ignoring water-covered regions (Table S1, Supplementary Information).

Climate data

This study used two sub-scenarios to understand the impact of changes in weather patterns on duckweed yields due to: (1) global warming and (2) nuclear winter. The rationale behind using these specific sub-scenarios was to assess duckweed's resilience to climate change and to parallelly comprehend its potential to be used as a post-disaster emergency crop. The former scenario corresponds to a gradual and relatively smaller shift in climate, whereas the latter scenario is used to represent a sudden and significant change in climatic conditions. The temperature and shortwave solar radiation data utilized for running these scenarios are described in the following sections (Sects. "Climate change scenarios" and "Post-nuclear war scenarios") and are summarized in Table 1. The resulting data sets were used as input for the duckweed growth model (described in Sect. "Duckweed growth model").

Climate change scenarios

Climate data for the years 1981 to 2050 were obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) database that provides climate impact data across different sectors and scales [39]. The data set used for this study contains the Coupled Model Intercomparison Project Phase 6 (CMIP6)-based bias-adjusted atmospheric input data for the ISIMIP3b simulation round (updated on Feb 2, 2022). We specifically utilized the GFDL–ESM4 global circulation model

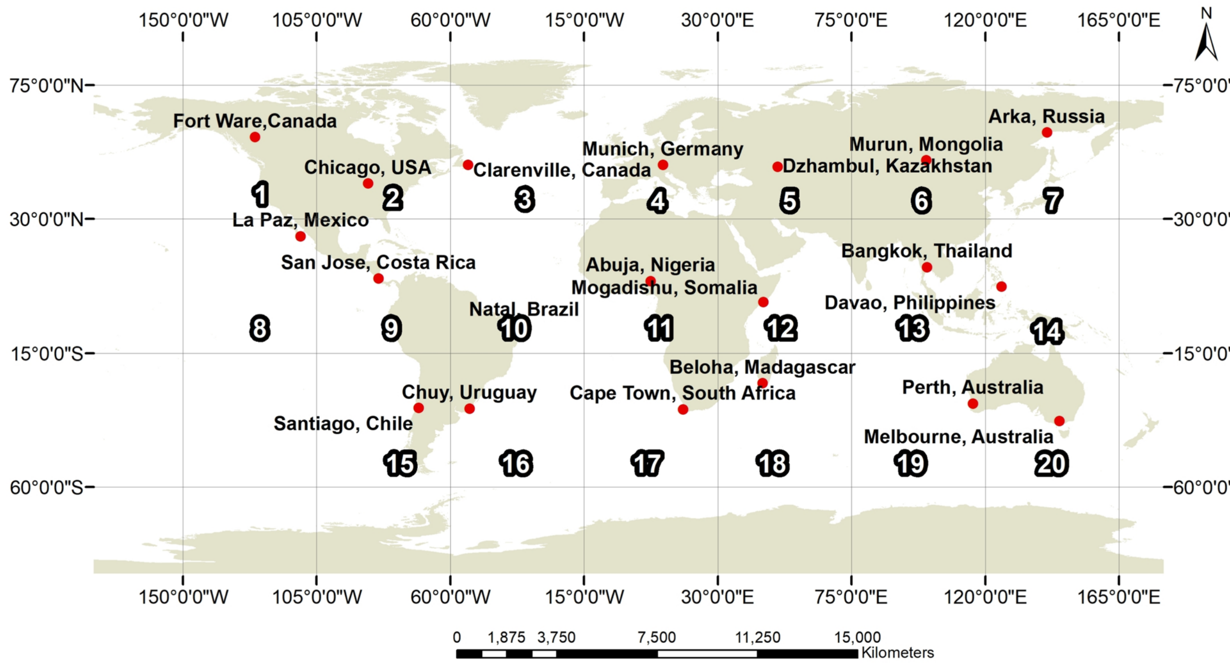

Fig. 1 Spatial geographic grids and discrete locations (red dots) selected for duckweed yield simulations

Table 1 Global warming and nuclear winter scenarios considered in the study to assess impacts on duckweed yield

Scenario		Model/data source	Number of years used	Reference
Global Warming	Baseline	GFDL–ESM4 model data from CMIP6 (using ISIMIP3b protocol)	34 years (1981–2014)	
	SSP126/RCP2.6 (Low GHG)		36 years (2015–2050)	[39]
	SSP585/RCP8.5 (High GHG)		36 years (2015–2050)	
Nuclear Winter	Baseline	ModelE (5 and 47 Tg); WACCM4 (150 Tg)	19 years (with nuclear war occurring in year 5)	[15], Toon et al. [66]
	Target01 (5 Tg soot injection)			
	Target05 (47 Tg soot injection)			
	Target07 (150 Tg soot injection)			

SSP Shared socioeconomic pathways, *RCP* Representative concentration pathways, *GHG* Greenhouse gases, *ISIMIP* The Inter-Sectoral Impact Model Intercomparison Project, *GFDL–ESM4* Geophysical Fluid Dynamics Laboratory Earth System Model 4, *CMIP6* Coupled Model Intercomparison Project Phase 6, *GISS* Goddard Institute for Space Studies, *WACCM4* Community Earth System Model–Whole Atmosphere Community Climate Model-version 4

(Geophysical Fluid Dynamics Laboratory Earth System Model) as the climate forcing and generated different climatic variables, including surface downwelling shortwave radiation (in W m^{-2}) and temperature (minimum and maximum; in K (Kelvin)) at a high spatial resolution of $0.5° \times 0.5°$ [16]. The duckweed model presented in Sect. "Duckweed growth model" incorporated mat density, photoperiod, and nutrient concentrations as the key drivers of duckweed growth (in addition to temperature and light intensity). However, there is no data to capture the variability of these factors under different climate change scenarios. While the model accounts for changes in photoperiod based on geographic location (latitude and longitude), its representation of how photoperiod may shift with climate change is limited by the available data. Furthermore, nutrient availability and mat density are assumed to remain constant over time across all locations.

To make comparative impact assessments, we utilized data corresponding to two future global warming scenarios or Shared Socioeconomic Pathways (SSP). These pathways combine socioeconomic factors with anticipated emission trajectories caused by greenhouse gases (GHGs) in the atmosphere, which is also known as a Representative Concentration Pathway (RCP). In addition to a historical/baseline case, two SSPs were used: (1) SSP126, an optimistic scenario with RCP 2.6 (low GHGs), assuming radiative forcing reaches 2.6 W/m^2 by the year 2100, and (2) SSP585 with RCP 8.5 (high GHGs), representing the worst-case scenario with an additional radiative forcing of 8.5 W/m^2 by 2100 [23, 55]. Historical observational data were used for the years 1981–2014, and climate change projections spanned the subsequent 36 years from 2015 to 2050 (Table 1).

Post-nuclear war scenarios

Climate data utilized for post-nuclear war atmospheric cooling (also called nuclear winter) scenarios corresponded to potential outcomes of different scale nuclear wars. The data cover nuclear winter responses simulated using two models: (1) ModelE developed by National Aeronautics and Space Administration Goddard Institute for Space Studies (GISS) [60, 66] and (2) the Community Earth System Model–Whole Atmosphere Community Climate Model-version 4 (WACCM4) [15]. A range of four different scenarios was considered with varying amounts of soot injected into the atmosphere (Table 1): (1) control or baseline; (2) 5 Tg; (3) 47 Tg; and (4) 150 Tg. The three nuclear war scenarios are labeled Target01, Target05, and Target07 in increasing order of soot injections, as reported in the original simulation studies. The Target01 (5 Tg) and Target05 (47 Tg) cases correspond to an India–Pakistan war [66], whereas the Target07 (150 Tg) case involves a war between the United States and Russia [15]. The simulations utilizing ModelE generate outputs with a spatial resolution of $4^\circ \times 5^\circ$, whereas WACCM4 has a resolution of $1.9^\circ \times 2.5^\circ$. Since this is a slightly coarser resolution than the global warming data, the locations inside the 20 grids were slightly adjusted from those identified in Sect. "Climate change scenarios" (Table S2, Supplementary Information). The number of simulation years provided by the models varied between the four post-nuclear war scenarios. Therefore, for consistency and fair comparisons, we only selected 15 years of data after the nuclear war for all four scenarios (Control and Targets 01, 05, and 07). Year 1, in this case, was the year the soot injection occurred, when black carbon was assumed to be injected over a 1-week period starting 15 May in year 5 in agreement with nuclear war scenarios [15]. Similar to the global warming simulations, we extracted shortwave radiation and air temperature (minimum and maximum) data from these simulations to run the duckweed growth model under post-nuclear war scenarios.

Model framework

For using the climate data in the duckweed growth model, some unit conversions were required: (a) shortwave radiation values were converted to photosynthetically active radiation (PAR; in μmol m^{-2} s^{-1}) using a conversion factor of 2.02 (1 W m^{-2}=2.02 μmol m^{-2} s^{-1}) [45] and (b) daily temperatures were converted to units of °C. PAR corresponds to the portion of the solar radiation spectrum that plants use for photosynthesis and is, therefore, a better input for the growth model than the shortwave radiation. Data processing was carried out using MATLAB® programming software to create climate files in a format suitable for running the duckweed growth model in R. The model outputs annual duckweed yield for all the years in both global warming and nuclear winter scenarios. It uses mean daily temperatures, calculated by averaging maximum and minimum temperatures for each day of the year. The modeling framework built in R reads temperature and light intensity data for the respective climate scenario and uses it for simulating annual duckweed yield for each grid and each year (Fig. 2).

Output files from the model provide the amount of duckweed produced on a daily scale and the cumulative harvest over an entire year. Subsequent analyses involved studying changes in duckweed yields and fluctuations in growing seasons and GDD for the different locations considered. To narrow down the analysis to focus on the extreme ranges of GDD fluctuations, we selected nine grids out of the 20, each representing a specific region around the globe. Grids 1, 4, and 7 were chosen to represent the northern regions (far west, center, and far east locations). Similarly, Grids 8, 11, and 14 represent the equatorial regions, and Grids 15, 17, and 20 refer to the southern regions.

For the growing season trend, we plotted duckweed yields (in g/m^2/day) against the day of the year for all the years considered. Overall trends in growth curves were visualized using a smoothing method called the generalized additive model (GAM). Daily GDD for duckweed was calculated as done typically for agricultural crops using Eqs. (4)–(6) [51]. A lower temperature threshold of 5 °C and an upper temperature threshold of 35 °C were assumed for the calculations based on literature values [40, 58]. All the GDD values reported in the Results (Sect. "Results and discussion") refer to annual GDD cumulated over an entire year. We used Analysis of Variance (ANOVA) tests to determine the statistical significance of how variables such as GDD change when compared across different scenarios. Correlations between yield changes and annual GDD under the different climatic scenarios were also examined to identify any significant associations:

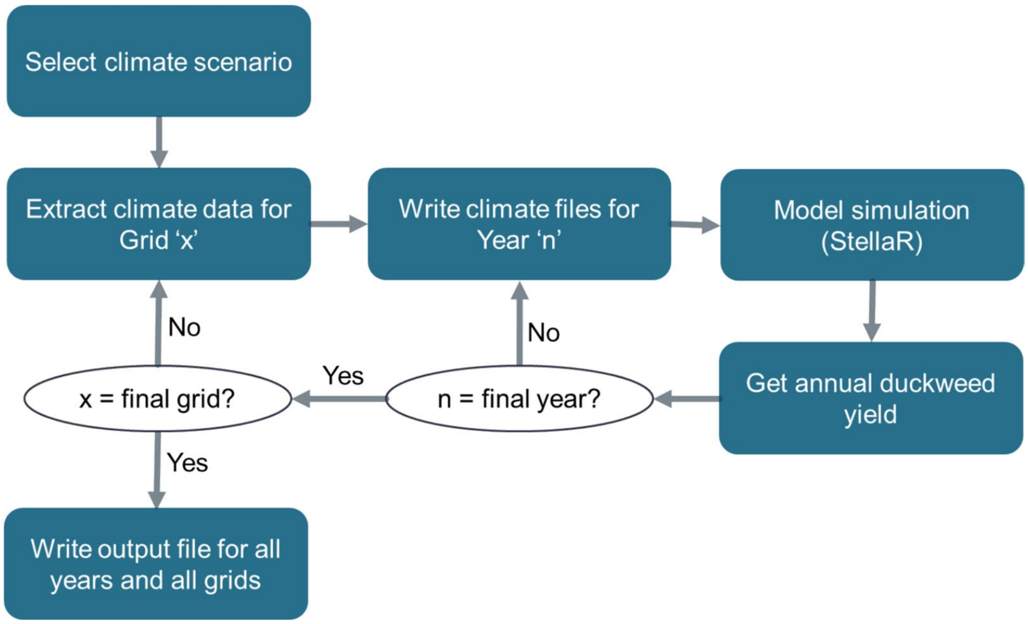

Fig. 2 Process diagram showing the flow of algorithms in the R model for simulating annual duckweed yields

$$\text{If } T_{\min} > T_{\text{base}_{\text{low}}}, \text{GDD} = T_{\text{mean}} - T_{\text{base}_{\text{low}}}, \text{ where } T_{\text{mean}} = \frac{T_{\min} + T_{\max}}{2} \tag{4}$$

$$\text{If } T_{\min} < T_{\text{base}_{\text{low}}}, \text{GDD} = T_{\text{mean}} - T_{\text{base}_{\text{low}}}, \text{ where } T_{\text{mean}} = \frac{T_{\text{base}_{\text{low}}} + T_{\max}}{2} \tag{5}$$

$$\text{If } T_{\max} > T_{\text{base}_{\text{high}}}, \text{GDD} = T_{\text{mean}} - T_{\text{base}_{\text{low}}}, \text{ where } T_{\text{mean}} = \frac{T_{\min} + T_{\text{base}_{\text{high}}}}{2} \tag{6}$$

Here, $T_{\min}$ = Minimum daily temperature; $T_{\max}$ = Maximum daily temperature; T_{mean} = Average daily temperature; $T_{\text{base}_{\text{low}}}$ = Lower temperature threshold of duckweed (5 °C); and $T_{\text{base}_{\text{high}}}$ = Higher temperature threshold of duckweed (35 °C).

Results and discussion

Climate change scenarios

Duckweed yields

Average historical duckweed yields for the years 1981–2014 displayed a strong spatial trend, with equatorial grids simulating the maximum yields (28.2–30 metric ton/ha/year) (Fig. 3a). This was closely followed by the southern grids (18.2–29.3 metric ton/ha/year), and the lowest possible yields were observed in locations within the northern hemisphere (0.9–11.8 metric ton/ha/year). Most of these values are in agreement with typical duckweed yields (10–30 metric ton/ha/year) attainable under real-world conditions [42]. Longitudinally, the central regions (Europe/Africa) have climates better suited for peak duckweed production compared to the far-east and far-west grids.

Model simulations with RCP scenarios revealed that equatorial regions are negligibly impacted in terms of duckweed production for both low (RCP 2.6) and high (RCP 8.5) GHG concentration scenarios (Fig. 3b). Even for the higher GHG scenario, the changes in duckweed yields were from − 1.87 to 0.77% (equating to − 0.54 to 0.22 metric ton/ha/year in absolute terms) for equatorial grids (Table 2). This slight decrease in yields for the tropical regions (Grids 9–13) is expected, given that the high temperature increases in these regions due to global warming can inhibit duckweed growth. Studies demonstrating severe effects on duckweed growth above 35 °C corroborate this finding [58, 67].

All locations in the colder northern region (except for Grid 1) interestingly showed an increase (up to 90%) in duckweed yields with the global warming scenarios, owing to the rise in temperatures that made the conditions more appropriate for duckweed growth (Table 2). This would substantiate existing evidence about the

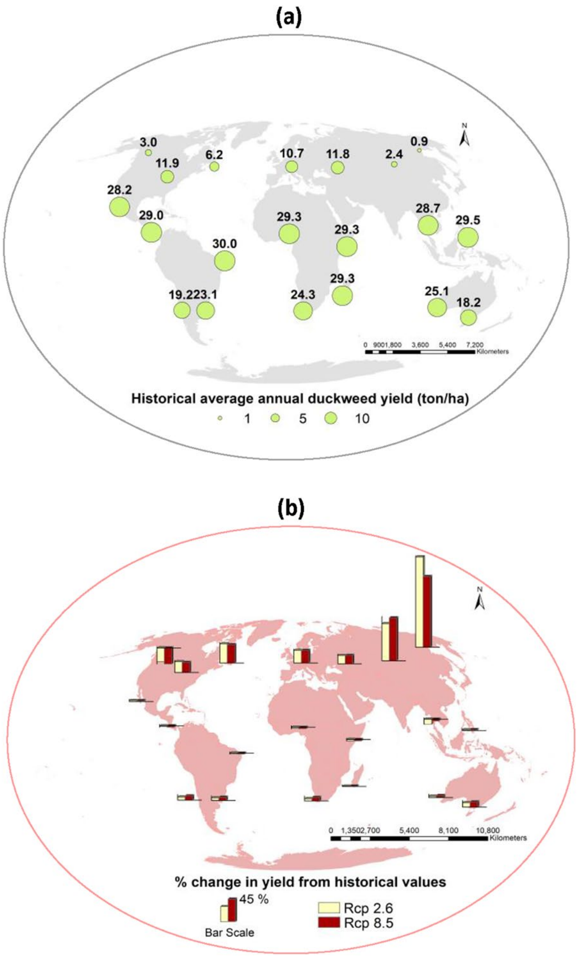

Fig. 3 **a** Annual average duckweed yields with historical data (1981–2014) and **b** percentage change in yields estimated with global warming scenarios (2015–2050) compared to historical yields

poleward migration of plant species due to global warming [37, 53]. While the SSP scenarios showed increased temperatures for Grids 2–7, the global warming impact on the Grid 1 location is different, where temperatures drop below historical averages, resulting in less-than-optimal conditions for duckweed. Detailed analysis of temperature changes affecting duckweed's GDD is explained in the following section. Southern grids also showed an increasing yield trend, although the difference was very narrow (0.25–5.31%). Increasing spring temperatures and a lower occurrence of severe winters in the future could potentially explain the higher yields, especially in the colder northern regions [27]. A previous modeling study of global warming impacts on duckweed also demonstrated that the chance of duckweed dominance in drainage ditches increased from 33.3 to 66.7% under future climate scenarios [49]. In this study, overall, the average changes in annual yields were within the range of − 1.44 to 1.34 metric ton/ha/year for all grids and global warming scenarios considered. This highlights duckweed's resiliency to a changing climate and its ability to sustain reasonable yields even when exposed to varying weather conditions.

On further analysis of the year-to-year differences in yields (Fig. 4), it was evident that equatorial grids showed minor variations in yields compared to the average historical values (− 2.7 to + 2.2% with RCP 2.6 and − 3.8 to + 3.1% with RCP 8.5). The southern locations displayed slightly higher variability: − 1.4 to + 12.6% and − 0.4 to + 12.9%, respectively, with RCP 2.6 and RCP 8.5. The most noticeable annual variability could be observed in the northern locations, with Grids 1 (Canada) and 4 (Germany) showing variability in the range of − 61.7

Table 2 Absolute change in average annual duckweed yields for different global warming scenarios with cell color gradient showing the change from historical values in different geographic grid locations

	Global Warming Scenario	Change in average annual duckweed yield from historical values (metric ton/ha/yr) -1.5 … 1.5						
		Grid						
		1	2	3	4	5	6	7
Northern Grids	SSP126/RCP 2.6	-0.41	1.28	1.18	1.35	0.98	0.88	0.81
	SSP585/RCP 8.5	-0.48	1.22	1.14	1.34	1.00	1.02	0.63
		Grid						
		8	9	10	11	12	13	14
Equatorial Grids	SSP126/RCP 2.6	0.24	-0.33	-0.23	-0.28	-0.40	-1.44	0.20
	SSP585/RCP 8.5	0.22	-0.41	-0.29	-0.42	-0.41	-0.54	0.24
		Grid						
			15	16	17	18	19	20
Southern Grids	SSP126/RCP 2.6		0.58	0.59	0.51	0.07	0.36	0.81
	SSP585/RCP 8.5		0.82	0.76	0.83	0.09	0.51	0.97

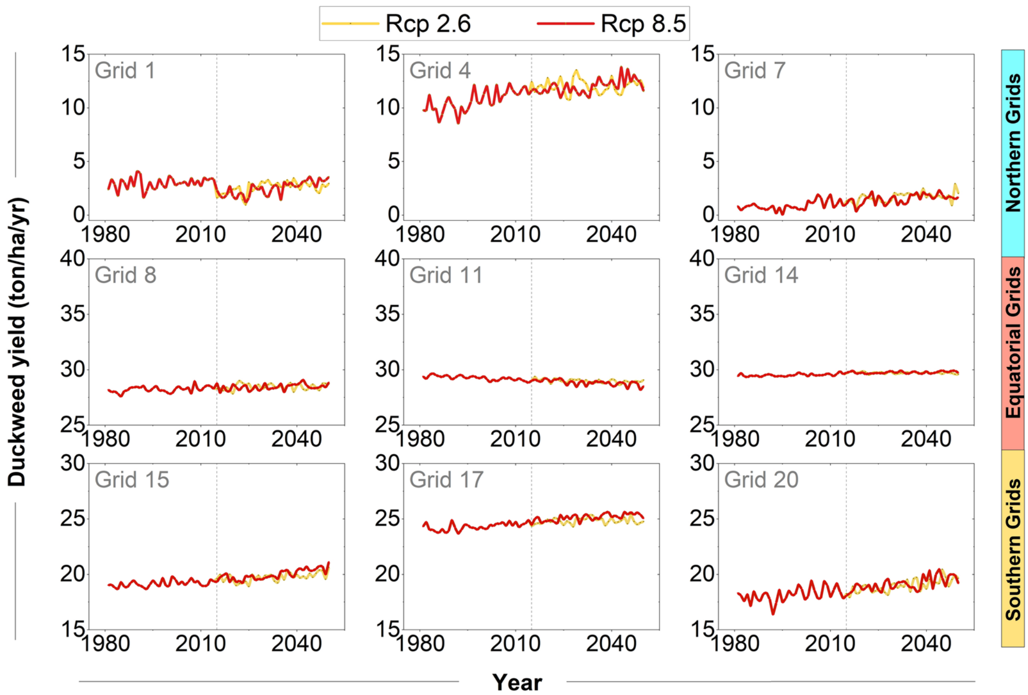

Fig. 4 Annual duckweed yields for historical (1981–2014) and global warming (2015–2050) scenarios for selected northern (top row), equatorial (middle row), and southern (bottom row) geographic grid locations

to + 22.1% and + 0.9 to 29.9%, respectively. The farthest grid in the eastern hemisphere (Grid 7 in Russia) expectedly showed the biggest change in yield (− 19.9 to + 231.8%). The forecasted warmer temperatures in this region, which otherwise faces extreme cold conditions, would prove beneficial for growing plants like duckweed in the future. It has been established that an increase in winter temperatures in these regions would favor increased production of grain crops [4, 26]. However, due to extreme temperatures and substantially less precipitation volume in the summer, a negative impact of global warming on crop productivity is probable with conventional crops, such as wheat and barley [6].

All of the locations except those in Grids 1, 8, and 11 showed an increasing trend in annual duckweed yield for more than 30 out of the 36 years simulated with the SSP scenarios. Grid 1 (in Canada) had reduced yields for most of the years (20 of 36). Even though Grid 11, simulated for a location in Nigeria, showed a decrease in yield for almost all years, the differences were marginal (up to − 3.8%). It is imperative to study yearly trends in agriculture-related global warming studies to ensure that the crop shows reasonable yield stability over a longer time span. This would further play a vital role in improving food security by avoiding supply–demand fluctuations and boosting the confidence of farmers in deciding to implement new cropping systems. Together with the results pertaining to annual average yield variability, the minor variations in temporal yield trends underscore duckweed's climate resilience, especially in equatorial and southern regions.

Growing season and growing degree days

Visualizing daily duckweed biomass accumulation over an entire year helps understand changes in the growing season when simulated with different global warming scenarios. Like the findings in Sect. "Duckweed yields", yields simulated for locations in Grids 8–20 (equatorial and southern regions) had very similar growing season trends with historical and SSP scenarios (Fig. S1, Supplementary Information). For Grid 1 (Canada), biomass harvesting (beyond the accumulation threshold of 99 g/m^2) starts between days 188 and 227 for the historical years 1981–2014. However, with global warming, the harvesting initiates between days 195 and 236, showing a slight lag in the growing season, contributing to lower yields than historical averages. This is attributable to the predicted lower temperatures with SSP scenarios in this region. Grids 4 (Germany) and 7 (Russia) showed a contrasting trend, where the duckweed accumulation gets an earlier start (during days 111–159 versus 126–171 with historical data). This agrees with a past study demonstrating that under global warming, duckweed dominance in the Netherlands (representing Grid 4) would start 5–23 days earlier, depending on the GHG emission scenario and nutrient availability [49]. The same research also showed extended dominance, and hence higher yields, occurring with increasing temperature—similar to our results described in Sect. "Duckweed yields".

Early planting is a beneficial outcome of global warming in places like the Great Plains of the U.S., where yield increases of up to 53% have been reported in maize production owing to warmer spring temperatures [35]. However, on the other hand, rainfed crops with spring planting and fall harvest could see a decline in yield with reduced occurrence of summer rainfall and a higher probability of heat waves [59]. Duckweed may not see such harmful effects from reduced rainfall since it can be grown in very low water depths (< 10 cm) [3]. The early start of duckweed accumulation we observed in this study could also be compared to the global warming-induced early onset of algal blooms in Lake Washington, USA [71]. Considering that the duckweed growing season changes yearly, even with historical data, the differences in the growing season noted here are minimal. A reasonable conclusion here is that the small change in growing season initiation has a low impact on annual duckweed yields.

Out of the nine grids, only Grid 1 showed a decrease in GDD with global warming (972 for historical data, 800 for RCP 2.6, and 788 for RCP 8.5), which matches its lower yields under RCP scenarios (Fig. 5a). All other grids showed higher values of GDD with both RCP 2.6 (152–284 more than historical) and RCP 8.5 (146–305 more than historical) scenarios. Studying the distribution of GDD and their variance provides valuable information on how much the GDD fluctuates over the entire simulation period. For example, the plot of Grid 4 (Fig. 5a) reveals that with global warming, the GDD distribution becomes much narrower than historical data, highlighting greater stability in yield responses with future climatic conditions. A two-factor ANOVA showed no significant differences between the ranges of GDDs (maximum–minimum) obtained across the three scenarios (p-value > 0.05).

The relationship between crop yield and GDD has been well-documented in the past, with most studies showing a positive linear or quadratic relationship [54, 62, 64]. Using all the data points (from three scenarios), a positive linear relationship was found between annual duckweed yield and GDD for all grids except the equatorial ones (Adjusted-R^2 for the curve fit = 0.84–0.96; Fig. 5b and Table S3, Supplementary Information). The high values of positive slope for the curve fit is a promising finding in the context of global warming, further highlighting that rising temperatures and subsequent increases in GDD in these locations would benefit crops like duckweed. While Grids 8 and 11 (in Mexico and the Philippines, respectively) displayed a relatively flatter regression slope (Adjusted-R^2 = 0.60–0.72), Grid 11 (in Nigeria) had a negative slope, supporting the harmful effect of extremely hot temperatures or very high GDD on duckweed yield. This is in agreement with other studies demonstrating that the yield responses of many crops tend to plateau or even go lower after striking a certain GDD threshold [36, 44, 63]. Our analysis showed that for duckweed, this threshold is reached when the GDD hits 7500–8000 units.

Nuclear winter scenarios

Duckweed yields

The soot injections from a nuclear war would result in more significant far-from-normal temperatures worldwide compared to the gradual temperature changes due to global warming. Hence, the analysis with post-nuclear war scenarios presented here is a measure of duckweed's resilience or vulnerability to extreme drops in temperature and light intensity. Overall, with increasing soot injections from Target 01 to 07 scenarios, duckweed yields were reduced across all the grids (Fig. 6 and Table 3). Equatorial grids showed the highest resiliency with minimal yield changes compared to the control scenario ranging from: − 0.36 to 0.16% with Target 01; − 4.68 to − 1.06% with Target 05; and − 21.14 to − 7.66% with Target 07. In this case, the absolute maximum decreases in yield were − 5.03 and − 6.43 metric ton/ha/year for Grid 11 (Nigeria) and 13 (Thailand), respectively. As noted by Peeters et al. [49], duckweed phenology does not change much due to global warming in tropical regions as the rise in temperature is smaller compared to temperate and boreal regions. The same rationale can be applied to the nuclear winter scenarios, where the decreases in temperatures in equatorial regions are well within the optimal range of duckweed growing conditions. Hence, the impact on yields is marginal in these locations.

Southern regions also showed yield resiliency with Target 01 (− 3.06 to 0.01% change), but demonstrated slightly elevated yield loss with Target 05 (− 23.63 to −7.54%) and Target 07 (− 41.49 to − 19.48%). The highest impacts on yield were found in the northern regions, which are expected to face extreme cold and dark conditions after a nuclear war. The changes in yields from historical values in Grids 1, 3, and 7 were in the range of − 26.42 to − 5.22% (Target 01), − 75.83 to − 38.28% (Target 05), − 82.3 to − 53.4% (Target 07). In absolute terms, these would amount up to a loss of 8.93 metric ton/ha/year in duckweed production; the highest reductions were seen in Grids 3 (USA) and 5 (Kazakhstan), which under normal conditions would otherwise produce

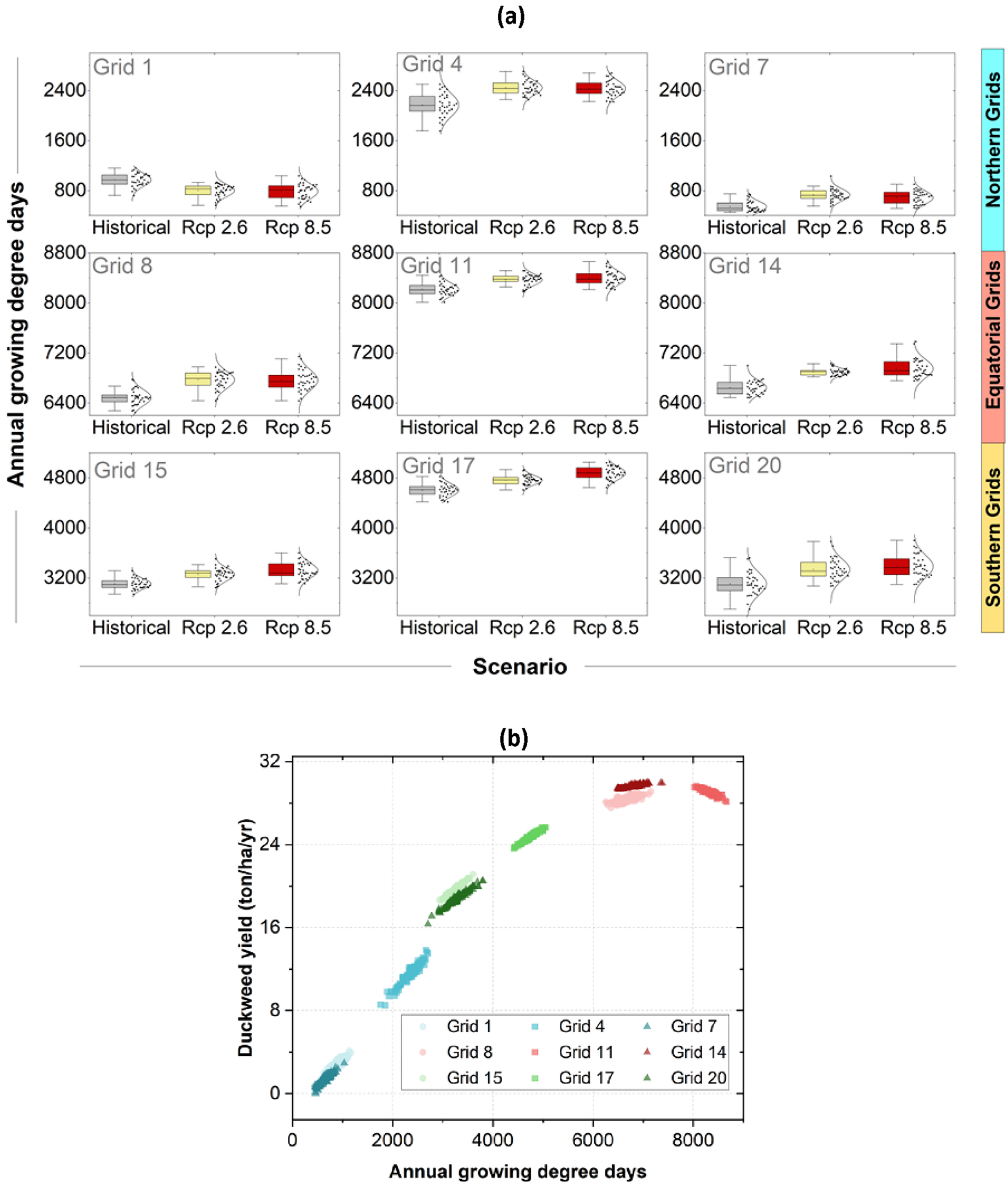

Fig. 5 **a** Growing degree days (GDD) of duckweed for selected northern (top row), equatorial (middle row), and southern (bottom row) geographic grid locations with historical and global warming scenarios; **b** relationship between annual duckweed yield and GDD displayed using data points from all three scenarios

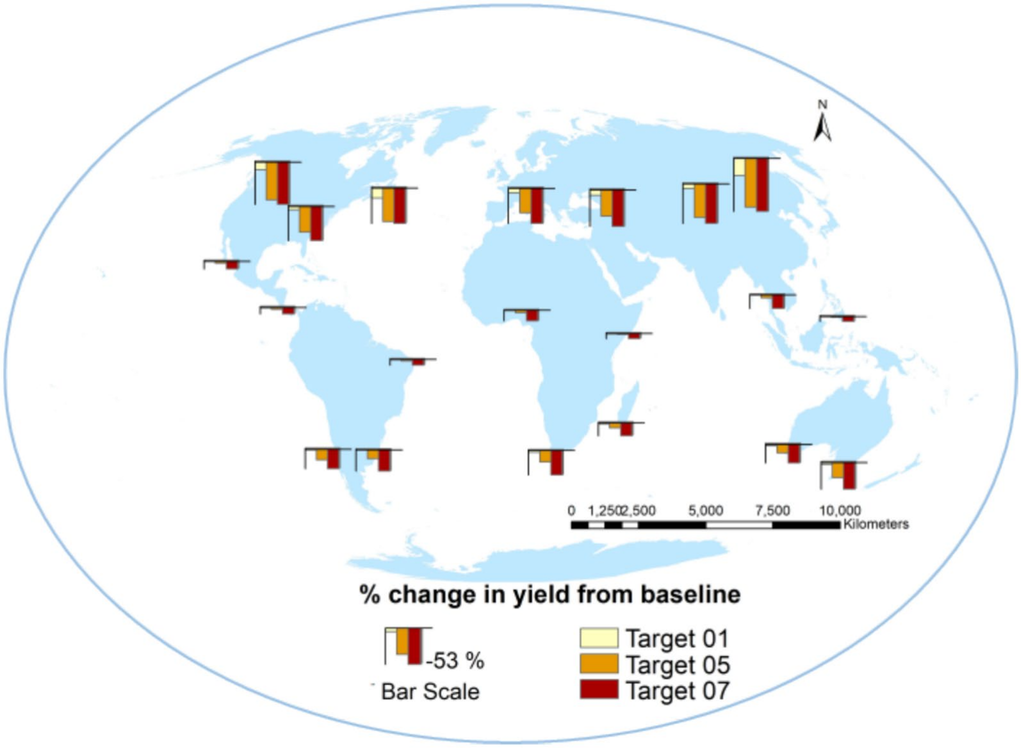

Fig. 6 Change in annual duckweed yields estimated with nuclear winter scenarios (averaged for 15 years after the war, with year 1 being the soot injection year) compared to that of a control scenario for different geographic locations

Table 3 Absolute change in average annual duckweed yields for different nuclear winter scenarios with cell color gradient showing the change from baseline values for each geographic grid location

		Change in average annual duckweed yield from baseline values (metric tons/ha/yr) -10 … 10						
	Nuclear Winter Scenario	Grid						
		1	2	3	4	5	6	7
Northern Grids	Target01	-0.42	-0.87	-1.38	-0.70	-1.30	-0.28	-0.39
	Target05	-2.10	-6.67	-4.64	-3.73	-6.32	-1.96	-1.13
	Target07	-2.34	-8.93	-4.87	-5.35	-8.80	-2.31	-1.22
		Grid						
		8	9	10	11	12	13	14
Equatorial Grids	Target01	0.05	-0.11	-0.03	-0.09	-0.02	0.01	0.01
	Target05	-0.90	-0.80	-0.60	-1.09	-0.40	-1.42	-0.33
	Target07	-3.59	-3.01	-2.64	-5.03	-2.45	-6.43	-2.35
		Grid						
			15	16	17	18	19	20
Southern Grids	Target01		-0.23	0.00	-0.66	-0.35	-0.50	-0.65
	Target05		-3.67	-3.65	-4.57	-2.26	-3.38	-5.02
	Target07		-6.63	-8.67	-9.88	-5.83	-7.34	-8.81

approximately 15–16 metric ton/ha/year of duckweed biomass. With a 27 Tg nuclear war scenario, Xia et al. [74] found that some mid to high-latitude regions could experience overall calorie reductions of 30–86%, while the lower latitudes are relatively less impacted with < 10% calorie reduction. As per the Xia et al. study, a 150 Tg

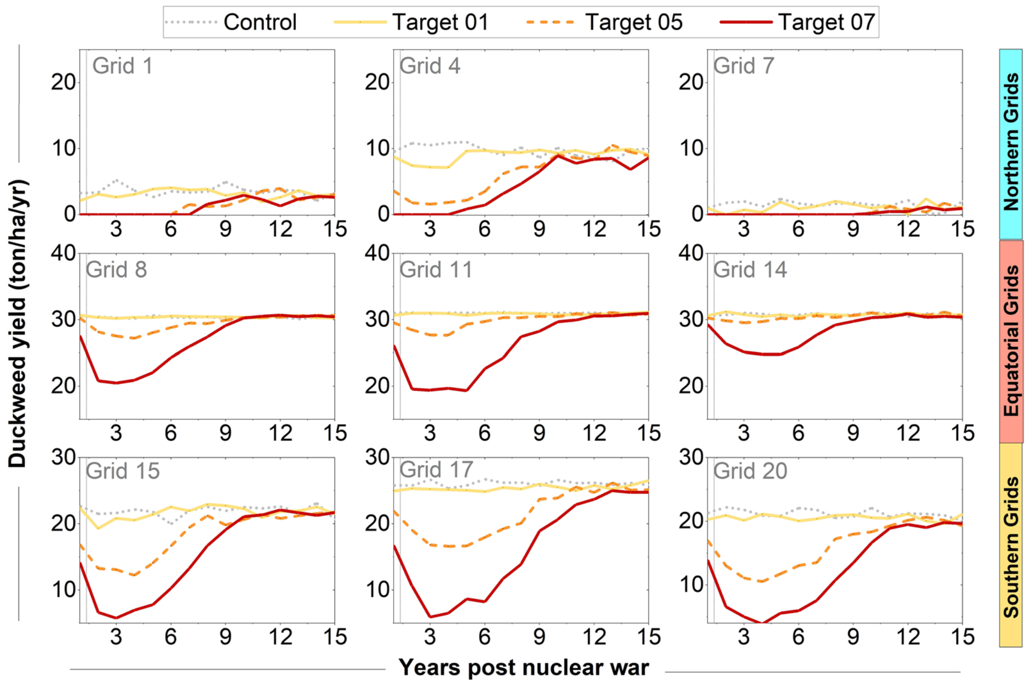

Fig. 7 Annual duckweed yields for nuclear winter scenarios (year 1 here indicates the year of soot injection) for selected northern (top row), equatorial (middle row), and southern (bottom row) geographic grid locations

case would almost result in up to 100% yield reduction in northern countries. Considering that international trade would be severely affected in these circumstances, even small amounts of locally grown emergency crops like duckweed would hence be beneficial.

Most of the harmful consequences of a nuclear war are typically felt in the immediate years following the war. Hence, a temporal yield comparison (Fig. 7) better explains the change in duckweed response to temperature and light intensity fluctuations. With a 5 Tg soot injection (Target 01), negligible yield changes were observed in all locations. However, evidently, for all the grids, duckweed yield dropped significantly in the first 5–6 years after the two highest soot injections before showing an increasing trend that ultimately stabilized to the normal yield values. In Fig. 7, the changes are relatively less apparent in northern grids (especially Grid 1 and 7), where the regular yields are already below 5 metric ton/ha/year. Grid 4 (Germany) yields are expected to touch zero in the first 4 years after the war. In addition to limiting weather conditions, one factor attributing to this could be the harvest threshold parameter in the model, which forces harvest to occur only if the biomass production surpasses 99 g/m^2/day. Under extreme cold and dark conditions, the duckweed may not reach this threshold to trigger a harvest, leading to zero annual yield. A similar post-nuclear war study predicting maize, rice, and soybean yields has shown that even the lowest soot injection (5 Tg) could decrease the average 5-year post-war yields by more than 75% in the high latitude regions [29]. Hence, there is value in leveraging duckweed's ability to maintain reasonable yields when exposed to low soot injections.

In the 150 Tg case, equatorial regions could see duckweed yields dropping up to 19–20 metric ton/ha/year in locations where typically a 30 metric ton/ha/year yield is expected. If only the average 5-year yield post-war is considered, equatorial grids would see 0.52–7.11% and 15.14–32.85% reduction with Targets 05 and 07, respectively. Considering that these are emergency post-disaster scenarios, where other conventional crops could fail to grow, it is promising to find that 19–20 metric ton/ha/year duckweed yields could still be produced to meet dietary protein requirements. Locations in the lowest latitudes (Grids 15–20) are projected to experience high yield loss for the Target 05 and 07 scenarios, causing yields to drop as low as 3.85–5.92 metric ton/ha/year. The large deviations from the control scenario yields (19.98–25.34 metric ton/ha/year) might be evidence that farming in these regions is highly vulnerable to extreme changes in climatic conditions. Five-year post-war average duckweed yields show up to 67% decline with the 150 Tg scenario. Under the 5 Tg case, the yield reductions in southern grids are in the range of 2.79–4.81%, which is significantly less than the 20–25% reduction observed for maize, rice, and soybean [29].

Growing season and growing degree days

Compared to the global warming scenarios discussed in Sect. "Climate change scenarios", nuclear winter conditions cause substantial changes in duckweed growing season trends and the number of GDD. The extreme deviations in temperature and light intensity accompanying the atmospheric soot injections, resulting in a cold and dark environment in many regions, can delay the start of the growing/harvesting season and shrink the GDD. Equatorial regions, which typically could see duckweed harvest starting around days 27–37, did not show noticeable differences in the growing season with the three soot injections (Fig. S2, Supplementary Information). However, the most intense nuclear war scenario (Target 07) tends to delay the harvest in these locations by almost a month in some cases (Grids 8 and 11). The effect of colder spring temperatures on seed germination of land-based crops, causing late planting and shorter growing seasons, is well-known [12, 61]. With duckweed, it is worth noting that even with delayed biomass accumulation, yields were within a reasonable range for equatorial locations. Southern regions showed comparatively higher deviations in growing seasons than equatorial grids, lagging the initial harvest by 13–46 days in some cases.

A major lag in duckweed harvest initiation was observed with increasing soot injection in the northern grids, which undergo drastic temperature drops immediately after a nuclear war. No harvests were triggered in Grids 1–7 during the immediate years after the war due to the biomass threshold not being met with Targets 05 and 07 (Fig. S2, Supplementary Information). The least affected northern location among the three grids studied was Grid 4 (Germany). Here, regular harvest patterns were observed with Targets 01 and 05 scenarios. At the same location, with the Target 07 soot injection level, the harvest was not triggered for the first 4 years post-war. This is slightly better than Grids 1 and 7 in the far east and far west, where it took 7–9 years for growing season trends to normalize.

Unlike the global warming scenarios, the impact of extreme weather conditions on duckweed GDD was clearly evident in the nuclear winter scenarios. The mildest nuclear winter scenario (Target 01) did not affect the duckweed GDD at any location. However, Targets 05 and 07 resulted in significant reductions in GDD (p value < 0.05) for all grid locations (Fig. 8a). While northern locations in Canada and Russia would remain nearly unaffected by the 5 Tg war, the same places would take around 6–9 years to return to normal GDD if exposed to 47 Tg or 150 Tg soot injections. The minimum GDD in the immediate years after the war could reach up to 3198–4300 in the equatorial regions, where the typical values are in the range of 7485–7980. Grids 15, 17, and 20 in the southern hemisphere are expected to be affected much more, with the GDD range decreasing from 3477–4855 to 574–885 in the first 6 years. To the authors' knowledge, this is the first study documenting GDD of duckweed; therefore, a direct comparison to existing literature values was not feasible. In comparing to conventional crops, mid-season corn typically requires a cumulative GDD of 2700 for optimal yields [47]. Although slight variations in this value are typical depending on the year and crop variety, GDD changing by 330 units could result in a 2-week difference in corn maturity date [38]. The statistical distribution of duckweed GDD shows that over the 15-year period, the average GDD values do not change considerably because all the locations see normal GDDs within 10 years after the war. However, the significant reductions in GDD and yield in the immediate 4–5 years after the war highlight the importance of having food reserves to meet nutritional demands during these times [24].

Figure 8b, which represents the GDD-yield relationship of duckweed for nuclear winter scenarios, indicates that the data points cover a wider range of the curve, including lower values of yields and GDD than those observed under global warming scenarios depicted in Fig. 5b. The underlying relationship remains the same as in Fig. 5b, but with additional data points in the lower ranges of GDD, we could observe overlaps between different geographic grids. For example, duckweed grown in locations along the equator would now show characteristics of southern locations. Similarly, in the first few years after the war, places such as Australia and South Africa would have GDD and yields representative of the northern grids. Similar to how global warming causes a northward migration of plant species [53], a substantially long nuclear winter may gradually result in a movement of plant species towards a more favorable climate in the tropical zone, although further research is needed to validate this. A linear relationship between crop yield and GDD, underlining the negative impact of shorter GDD on yield, is widely documented in the literature [32, 43, 70]. One study has shown that GDD variation could explain close to 30% of the change in maize yield [47, 75]. Figure 8b indicates that GDD can be used as an important variable to explain changes in duckweed yield.

Overall, our analyses infer that in the frigid regions of the northern hemisphere, duckweed alone may not be sufficient to meet human nutritional (protein) needs during a harsh nuclear winter. However, it can still be grown as a relevant protein source in other regions, yielding a

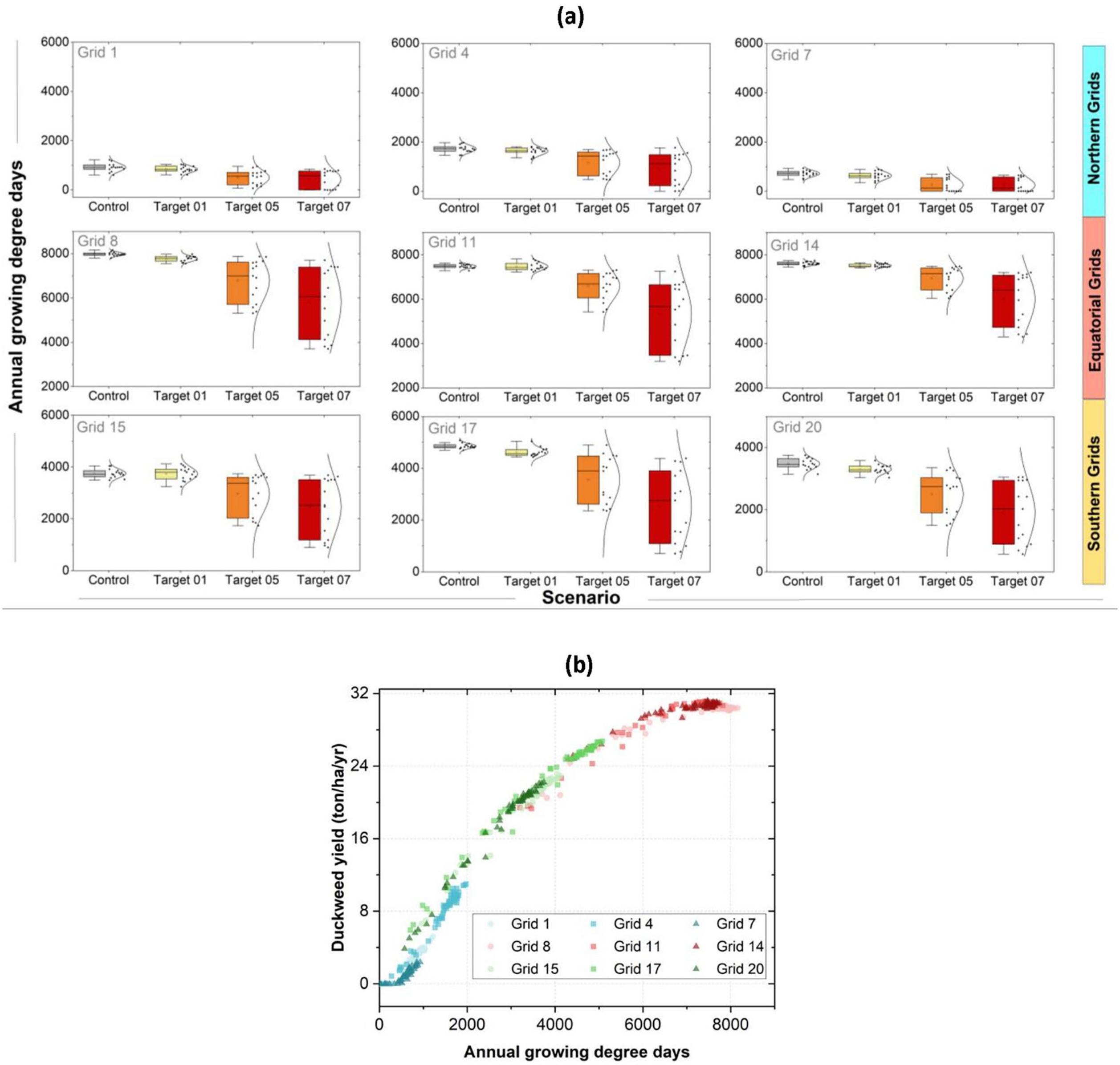

Fig. 8 **a** Growing degree days (GDD) of duckweed for selected northern (top row), equatorial (middle row), and southern (bottom row) geographic grid locations with control and nuclear winter scenarios; **b** relationship between annual duckweed yield and GDD displayed using data points from all four nuclear war scenarios

fair amount of biomass. Currently, livestock is one of the major sources of protein for humans, accounting for 39% of protein composition globally [17]. With nuclear winter causing severe disruption in livestock farming and assuming that most of the livestock feed in that situation would be diverted for human food, it is even more important to rely on high-yielding and resilient alternative protein sources [74]. Although energy access would be quite challenging under post-nuclear war scenarios, in a situation where indoor farming is feasible, duckweed could be an excellent food to grow with limited space and resources. A preliminary analysis showed that at a growth rate of 7 g/m^2/day [56], a two-person household can meet 20% of their annual protein needs by vertically farming duckweed in a four-tiered system with a footprint of 19.5 m^2, assuming an average protein requirement of 60 g per person daily. To meet the same 20% protein needs, 83.4 m^2 of soybean field or four times the duckweed area for outdoor pond cultivation would be needed (assuming 35% protein content for both duckweed and soybean, and considering annual soybean yield of 3 metric ton/ha). It's crucial to highlight that a plant such as duckweed may not offer all the necessary nutrients for survival. For instance, duckweed is low in fat content (~10%); therefore, a post-catastrophic diet may require a combination of diverse food sources to meet daily nutritional needs.

Comparison of scenario results

Our results indicate that global warming and nuclear winter scenarios have starkly different impacts on duckweed yields, both in magnitude and geographic distribution. Under global warming, yield changes were largely positive in northern regions, whereas tropical and equatorial regions experienced minimal change. In contrast, nuclear winter scenarios caused widespread yield reductions across all latitudes, with the most severe impacts in higher latitudes. While global warming generally expanded duckweed's viable growing range by increasing GDD in temperate and boreal regions, nuclear winter shortened or completely eliminated the growing season in these same locations due to extreme cooling. This highlights a key difference between the two climate extremes: global warming may enhance agricultural potential in some historically cold regions, while nuclear winter creates a universally hostile environment for plant growth, especially in the Northern Hemisphere. In addition, while low-emission nuclear war scenarios (5 Tg) produced similar yield trends to global warming—showing negligible impacts in tropical regions—higher soot injections (47 and 150 Tg) had far more severe consequences than even the worst-case global warming projections. For instance, while equatorial regions were resilient to both climate change and nuclear war, their duckweed yields were reduced by up to 21% under the most extreme nuclear winter conditions, compared to a maximum 3–5% change under global warming. Overall, the findings suggest that global warming could present opportunities for expanding duckweed cultivation in cooler climates, whereas nuclear winter would require more drastic adaptation measures, particularly in mid-to-high latitudes, where prolonged cold and low light conditions would make outdoor farming infeasible.

Socio-economic and logistical considerations for duckweed adoption

As climate change intensifies, the adoption of alternative crops like duckweed may become increasingly attractive; however, overcoming socio-economic and logistical barriers will be essential to its widespread implementation. Although duckweed as food is just gaining traction in Western countries, it has long been popular in many Asian countries including Thailand, Myanmar, and Laos [8]. However, public perception of duckweed as a viable food source may be hindered by its association with waste or its unfamiliarity in many regions. Promoting its benefits, such as sustainability and resilience to climate extremes, will be necessary to gain social acceptance and create market demand.

From a logistical standpoint, duckweed pond cultivation requires relatively simple infrastructure, making it a viable option for smallholder farmers in tropical and equatorial regions, where yields remain stable under both global warming and moderate nuclear winter conditions. There are also challenges related to harvesting and processing, especially for large-scale production, as current technologies for duckweed farming are underdeveloped in these regions, potentially increasing the cost of implementation. For household-scale farming, duckweed can still be a cost-effective food source, as the smaller initial investment and duckweed's fast growth cycle allow for multiple harvests per year.

In mid-latitude regions, where duckweed yields are projected to remain resilient, existing agricultural infrastructure could support large-scale production. Developing countries such as Brazil, China, and India are well-positioned to integrate duckweed into their existing wastewater-fed farming systems. However, processing facilities and supply chains need to be expanded to convert duckweed into commercially viable food and feed products. In northern latitudes, where global warming may enhance duckweed's growing season, but nuclear winter could significantly limit outdoor cultivation, controlled-environment farming (e.g., vertical farming) may be required for year-round production. These solutions are more feasible in wealthier economies, such as Europe, Canada, and the northern United States, where technological advancements and energy-efficient systems could make indoor farming cost-effective. However, high infrastructure and energy costs remain a barrier [52], necessitating policy incentives, subsidies, or integration with renewable energy sources to make duckweed farming more economically viable. Policy support and public/private sector investments, along with education on duckweed's sustainability and nutritional benefits, will be essential both for encouraging communities to adopt its cultivation and for fostering market demand and social acceptance.

Limitations and future scope

The work presented here comes with a few limitations, primarily stemming from the scale of the model simulations and the processes incorporated. The primary level of uncertainty comes from the use of a single climate model in this study (GFDL–ESM4). In addition, our analysis was constrained by the availability of nuclear winter data from only two models (ModelE and WACCM4), and the uncertainties associated with their projections of extreme nuclear winter could impact the duckweed yield results. Using additional climate models or an ensemble approach would provide a broader range of potential outcomes and improve confidence in the results. Future work should incorporate an ensemble of climate projections to better capture inter-model variability and enhance the robustness of yield predictions.

While the duckweed model accounts for various environmental factors influencing growth, it does not explicitly consider the effects of atmospheric CO_2 concentration on growth rate and yield. Given the importance of CO_2 in global climate change scenarios, incorporating its potential effects on duckweed growth could serve as a valuable extension of this work. In addition, the model was originally developed for controlled indoor simulations, whereas this study focuses on outdoor cultivation under natural climatic conditions. We addressed this limitation to some extent by integrating climate data, allowing for daily variations in temperature and light intensity. However, due to challenges in obtaining site-specific nutrient data, we assumed constant nutrient availability across all grids, which may not represent real-world variability. Duckweed growth is highly sensitive to nutrient concentrations, which can fluctuate due to factors, such as soil erosion, runoff, and wastewater inputs. Duckweed may exhibit faster growth rates in nutrient-rich environments (as long as it is not above the tolerance levels), while in nutrient-poor conditions, its productivity could be significantly lower than our model predictions. In addition, other environmental stressors, such as salinity, water pH, and competition with other aquatic species, could further influence duckweed growth. Variability in these factors may lead to local differences in yield that are not captured in our global-scale simulations. Field experiments and long-term monitoring data would be valuable in refining the model to better reflect real-world conditions. Future work could improve model predictions by incorporating more accurate nutrient data for different locations and scenarios. The climate change and nuclear war scenarios used in our simulations primarily examine the highest and lowest emission scenarios to cover the maximum range possible. For climate change, specifically, there could be value in using an ensemble of results from different climate change models and simulating additional SSP scenarios to get the full picture. Finally, studying outdoor duckweed cultivation under varying environmental conditions would provide an opportunity to compare actual growth rates with modeled results, enabling further refinement of the model to better predict yields in natural conditions.

Conclusions

This study examined the resilience of the duckweed plant to changing climatic conditions and extreme weather events such as those predicted to occur due to global warming or a nuclear winter. Spatial trend analyses revealed that duckweed production would be minimally impacted under future global warming in the low-latitude regions. Locations in the northern hemisphere are expected to see an increase in duckweed yield with warmer winters and longer growing seasons. A low-emission nuclear war would have low impacts on duckweed yield in most locations, except for the far-east and far-west northern geographic regions. For higher emission wars, the impacts would be felt even in the southern countries. Due to the high-yielding potential of duckweed, a reasonable amount of duckweed could still be produced in many locations under extreme environments. We found that the immediate years after the war are especially crucial for the high-latitude locations since the conditions are predicted to be unfavorable for producing enough duckweed to meet dietary needs. A substantial drop in cumulative GDD in 5–6 years after a war points toward the need for creating emergency reserves with multiple food sources.

Overall, the work presented here not only validates duckweed's tolerance to global warming but also provides insight into how an extreme disaster like nuclear war would impact global food production, and therefore, encourages us to find sustainable, resilient, and locally available food sources to enhance food security under such circumstances. With future model enhancements, incorporating additional growth variables and other plant species, the modeling framework presented here could be used for studying climate change and disaster-resilient crops. Future research should focus on field validation through large-scale cultivation trials and assess how variations in nutrient availability impact yield and nutritional composition. From a policy perspective, increased investment in duckweed-based farming initiatives is needed to integrate them into climate adaptation strategies, promoting their role in diversifying food production and reducing dependence on traditional staple crops.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40066-025-00527-2.

Supplementary Material 1.

Author contributions

P.V.F. developed the methodology, analyzed and interpreted the data, and wrote the initial draft of the manuscript. R.A.B. supervised the research, provided resources, and edited the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials
The data sets during and/or analyzed during the current study available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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