The Intensity of the Interaction Between Native and Non-native Antarctic Plants Depends on the Non-native Plant, Water Availability and Temperature.

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Research Article

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Abstract

Anthropogenic pressure and climate change have generated important changes in the environmental conditions of Antarctic ecosystems (e.g., arrival of non-native species, increase in temperature, precipitation, and ice-free areas), which can generate negative impacts on the native flora. Thus, we evaluated how the presence of the non-native plants *Poa annua* and *Juncus bufonius* could impact the native species *Colobanthus quitensis* and *Deschampsia* antarctica under climate change scenarios. Individuals of *C quitensis*/*D. antarctica* and *J. bufonius*/*P. annua* were subjected to four growth conditions: 6°C/low water availability (LW); 8°C/LW and 6°C/high water availability (HW) and 8°C/HW. We hypothesize that competition will be more intense at 8°C/HW, while at 6°C/LW the predominant interaction will be facilitation. Under 8°C/HW conditions all species significantly increase biomass production, but mortality of native species tends to increase. The relative interaction index (RII) showed a competitive effect of both non-native species on *D. antarctica*, independent of temperature and water availability, while for *C. quitensis* competition is more intense at LW. These results show that the effect of climate change could enhance the impact of non-native species on native species in Antarctic ecosystems, including non-native species that have been reported but do not have stable populations in the Antarctic Peninsula.

Introduction

The maritime Antarctic area during the last decades has been considered a pristine ecosystem, being an area that was free from the arrival of non-native species (Hughes and Convey 2011; Huiskes et al. 2014; Galera et al. 2018; Chwedorzewska et al. 2020). This low level of invasion is mainly determined by the low pressure of propagules because of existing geographical (Lee and Chown 2009; Hughes and Convey 2011) and physiological barriers (extreme climatic and edaphic conditions: low temperature, poor water conditions, strong winds, specific light regime, poor soil conditions) (Frenot et al. 2005; Convey 2011; Convey and Peck 2019; Hughes et al. 2020). However, during the last 50 years the increase in anthropogenic pressure, associated with scientific and tourist activities, and the effect of regional climate change (mainly the Antarctic Peninsula region) have changed this paradigm (Hughes et al. 2020). Events of the introduction of non-native plants propagules have significantly increased in maritime Antarctic, where human activities are concentrated and, where the climatic conditions are more suitable for the growth of plant species, compared to the continental Antarctic (Chown et al. 2012; Chwedorzewska et al. 2015; Molina-Montenegro et al. 2015; Fuentes-Lillo et al. 2017a; Bokhorst et al. 2021), altering the distribution and conservation status of native terrestrial flora.

The maritime Antarctic terrestrial ecosystem is characterized by presenting a simple community structure, composed of low diversity of *Magnoliophyta* (*Deschampsia antarctica* Desv., *Poaceae*, and *Colobanthus quitensis* (Kunth) Bartl., *Caryophyllaceae*) species and richness of cryptogams (Convey et al. 2014). These characteristics could facilitate the establishment and growth of non-native species (Convey and Smith 2006; Casanova-Katny and Cavieres 2012; Atala et al. 2019). Considering these characteristics, it has been suggested that maritime Antarctic, as they present low productivity, will present high invasibility

(Galera et al. 2018). This condition, in the future, could generate that a large percentage of non-native species manages to establish themselves in the Antarctic ecosystem. This establishes mainly associated with increases in propagule pressure via human´s vector, even if abiotic conditions exceed their range of climatic tolerance (Chown et al. 2012; Fuentes-Lillo et al. 2017a; Hughes et al. 2020; Bokhorst et al. 2021). Added to this, if we consider the current effect of global change processes (climate change and increased anthropogenic pressure) on the Antarctic ecosystem, the impact of non-native species could increase significantly during the next century (Duffy et al. 2017; Chwedorzewska et al. 2020; Hughes et al. 2020; Pyšek et al. 2020).

Climate suitability analysis for 93 invasive species worldwide, including species present in the sub-Antarctic and Antarctic islands, has shown that the climate can function as an abiotic filter for some non-native species, but there is a broad spectrum of non-native species, mainly herbaceous that are invading sub-Antarctic islands, that by 2100 could become established in the ice-free zones in the Antarctic Peninsula region (Duffy et al. 2017). It has recently been established that 16 non-native species of different growth forms have had been able to germinate and grow under simulated climate change conditions in Antarctic soils; This suggesting that the number of non-native species that can be established is higher than that determined by different distribution models (Bokhorst et al. 2021). Under this scenario, understanding how the synergies between climate change and anthropogenic pressure increase the risk of the establishment of non-native species and increase the impacts on the Antarctic ecosystem (and the change in biotic interactions between native and non-native species) is fundamental from a conservative perspective (Chown and Brooks 2019; McCarthy et al. 2019; Hughes et al. 2020).

The effect of climate change can improve the invasion process and change the existing biotic interactions between native and non-native species, but these changes and the invasion process facilitation are context-dependent and species-specific (Blumenthal et al. 2016). Under this context, the biotic interactions expected in Antarctic ecosystems will be mediated by the stress-gradient hypothesis, that under current extreme climatic conditions, the predominant interaction between plant species is facilitation, while under more suitable climatic conditions (due to climate change), competition is more intense among species (Lortie and Callaway 2006; Atala et al. 2019). Furthermore, the intensity of these interactions between native and non-native species can be influenced by different variables such as the growth temperatures (especially an increase in the number of cumulative days with temperature above 0^{o}C and the duration of the vegetation season; Cavieres et al. 2018), the phylogenetic closeness of the species (Dóstal et al. 2011), the functional traits (Cahill et al. 2008; Burns and Strauss 2012), the ontogeny of the species analyzed (LeRoux et al. 2013) and the phenotypic plasticity and genetically based trait differentiation (Alexander et al. 2016). Understanding these processes could improve our understanding of how biotic interactions (mainly competition) could increase due to climate change; and how through facilitative interactions, non-native species could establish and disperse under extreme climatic conditions that currently prevail in the Antarctic Peninsula (Brooker et al. 2008, Casanova-Katny and Cavieres 2012; Hughes et al. 2020; Rew et al. 2021).

It has been experimentally established that the impact of climate change can affect the functioning of both native and non-native species in Antarctic ecosystems (Molina-Montenegro et al. 2011, 2016, 2019; Torres-Díaz et al. 2016; Fuentes-Lillo et al. 2017b; Acuña-Rodríguez et al. 2017; Atala et al. 2019). Although progress has been made in understanding the competitive effect of *Poa annua* L. (the first alien plant that established functional population under Antarctic conditions) on native species (*C. quitensis* and *D. antarctica*), there are still no studies evaluating what would be the competitive effect of other non-native species reported in the ecosystems of the Antarctic Peninsula and even invade the sub-Antarctic ecosystems (Frenot et al. 2005; Duffy et al. 2017; Hughes et al. 2020) or their arrival could be *via* human activities (Fuentes-Lillo et al. 2017a).

One of the non-native species that would function as a model species in the analysis of the effect of climate change on growth, survival and the type of interaction (facilitation/competition) on native Antarctic plants is *Juncus bufonius* L. *J. bufonius is* a non-native species whose propagules have been reported in soil samples from the vicinity of the H. Arctowski Polish Antarctic Station (Admiralty Bay, King George Is., South Shetlands), with a probable distribution area of no more than 300 m^2 that includes from the meteorological station to the tourist sales store, in this area, there is a great anthropogenic disturbance (Cuba-Díaz et al. 2013, 2015). Additionally, this species has been reported invading different sub-Antarctic islands (Frenot et al. 2005), is considered one of the most dangerous species due to its high level of invasiveness (Convey et al. 2010; Bazzichetto et al. 2020).

Based on these approaches, this research evaluates the effect of climate change on the individual response and biotic interactions of native and non-native plants of the Antarctic Peninsula. It will seek to emphasize the competitive effect of non-native species (*P. annua* and *J. bufonius*) on native species (*C. quitensis* and *D. antarctica*). In this context we ask ourselves two questions: 1) How do simulated climate change conditions (increased temperature and increased water availability) influence biomass production and the mortality rate of native and non-native species? 2) How does the effect of simulated climate change influence the interactions between native and non-native species that coexist in Antarctic ecosystems? We hypothesize that the competitive effect of non-native species on native species will be greater with increasing temperature and water availability. Furthermore, due to the phylogenetic similarities between non-native species and *D. antarctica*, the competitive effect is expected to be greater for this native species. Additionally, we expect that under conditions of low temperature and low water content, facilitation will be the predominant interaction.

Methodology

Study species:

1400 individuals of four species present in maritime Antarctic were used, the two native: *C. quitensis* and *D. antarctica* and the two non-native: *J. bufonius* and *P. annua*, all collected in the vicinity of the H. Arctowski Polish Antarctic Station, King George Island, Antarctica (62° 09'S, 50° 28'W, 3-23 m a.s.l).

C. quitensis and *D. antarctica* were vegetatively propagated for a period greater than 6 months, while *J. bufonius* and *P. annua* were propagated from seeds collected from plants maintained in the laboratory under growth conditions indicated below. The *J. bufonius* seeds were germinated 2 months before the experiment, while those of *P. annua* were germinated two weeks before since their germination and growth is much faster than *J. bufonius* under controlled conditions.

All plants were kept until the beginning of the experiments in polystyrene containers of 240 cm^3 inside a growth chamber at a temperature of 13 ± 2°C, photoperiod of 16/8 hours light/dark, with a flow of photosynthetic photons of 100 ± 20 μmol photons m^{-2} s^{-1}, in a substrate formed by leaf soil: peat: perlite in the ratio 3:2:1 v/v, the relative humidity was 80 ± 20%, maintain with manual watering.

Growth response and mortality percentage of native and non-native species under a climate change scenario (Experiment 1)

To determine the influence of climate change on biomass production and percentage of mortality of the species *C. quitensis*, *D. antarctica*, *J. bufonius* and *P. annua*; individuals of each species were subjected to four different water and temperature conditions: 6°C/low level of water availability (LW); 8°C/ low level of water availability (LW) and 6°C/ high low level of water availability (HW).The temperature of 6°C simulates the current conditions of mean temperature in the growing season during the Antarctic summer (Turner et al. 2009, IPCC 2019), while the second temperature considers an increase to 8°C, based on estimators of moderate climate change indicating at least a 1.5°C-2°C increase for mean temperature (Duffy et al. 2017; Frame 2020; Hughes et al. 2020). Two used conditions of water availability simulate the current conditions LW (of an average of -20 KPa of water potential; (Molina-Montenegro et al. 2012; Torres-Díaz et al. 2016; Fuentes-Lillo et al. 2017b) and the projected conditions (of an average of -20 KPa of water potential) due to the increase in the precipitation level and thaw because of the temperature increase (Molina-Montenegro et al. 2012; IPCC 2019). The water content was regulated by manual irrigation every 48 hours to maintain the water potential of the soil at both -20KPa and -14 Kpa.

Ten individuals from each species under study were subject to the experimental condition described above. Each experimental conditions consisted of 10 replicates. Experiments were maintained under the experimental conditions for 2.5 months. At the end of this period, all individuals were collected and dried at 60°C for four days, then weighed in an analytical balance to evaluate the total biomass. (Cavieres et al. 2018). The number of dead individuals was evaluated during the entire experimental period, this variable was worked on as a percentage of mortality, which indicates the percentage of dead individuals based on the initial quantity.

Competition Experiments (Experiment 2)

To evaluate the effect of temperature and water availability on the interaction between native and non-native species, a competition experiment was conducted. The experiment consisted of individuals of *C. quitensis* (n=10) and *D. antarctica* (n=10) growing together with individuals of *J. bufonius* (n=10) or *P.*

annua (n=10), as control 20 individuals from each species growing separately, under the same conditions as described above. Additionally, the availability of nutrients was controlled with the application of a Hoagland solution. Each experimental condition consisted of 10 replicates and was maintained for 2.5 months in growth chambers. The biomass and the percentage of mortality were evaluated following the methodology described for experiment 1.

Data Analyses

All data analyses were run in R version 3.6.1 (R Core Team 2019).

Experiment 1

To determine the effect of temperature and water availability on biomass production and the mortality rate of each species, a two-way ANOVA was performed using the *aov* function, the growth temperature two levels (6°C and 8°C) and water availability two levels (LW and HW) and the interactions between both factors were the independent variables. To show significant differences between the different experimental conditions (temperature, water availability) a Tukey HSD test was performed. To normalize the mortality percentage data, this was transformed using the arcsine function of the root.

Experiment 2

To determine how the presence of individuals of non-native species, temperature and water availability affects the biomass and percentage of mortality of the native species, a three-way ANOVA analysis was performed, using aov function, where the growth temperature (6|C and 8°C), water availability (LW and HW), and the presence of non-native species (and the interactions of these variables were the independent variables. To determine significant differences between the different experimental conditions (temperature, water availability and presence of individuals of non-native species) a Tukey HSD analysis was performed. To normalize the data on the percentage of mortality, this was transformed using the arcsine function of the root.

To determine the intensity of the interaction between non-native and native species and the different experimental conditions the relative interaction index (RII) for biomass was used, which is a proxy that determines the intensity of the interaction (Armas et al 2004). Finally, to determine if the RII values differ from 0 and differences between the two levels of water availability for each temperature, a t-test was performed. All the graphs were made with the *ggplot2* package of the R program (Core Team 2019).

Results

Growth response and mortality percentage of native and non-native species under a simulated climate scenario (Experiment 1)

The results indicated that temperature had a significant effect on biomass production of the four species under study (Table 1, Fig. 1a-d) and that only for *J. bufonius* the water content showed a significant effect, with greater accumulation of biomass to HW (Table 1, Fig. 1c). High temperature favored the increase in biomass of the three species under study, except for *D. antarctica*, where it caused biomass decreased (Fig. 1b). The mortality of individuals was marginal, with values below 1% and only in *C. quitensis* this value was higher but without exceeding 10% mortality (Fig. S1 a-d). Regarding this variable, the influence of the environmental factors studied was differential, being the water content the factor that showed significant effects in *C. quitensis* and *J. bufonius*, while in *P. annua* the factor that exerted significance was the temperature, for *D antarctica* both factors and their interaction significantly influenced the mortality of their individuals (Table 2, Fig S1 a-d).

Table 1
Two-way ANOVAs on the effects of temperature (6°C or 8°C) and water availability (LW or HW) on biomass accumulation of native (*C. quitensis* and *D. antarctica*) and non-native (*J. bufonius* and *P. annua*) Antarctic vascular plants.

Mortality	**Factors**	**Df**	**SS**	***F***	***p***
	Temperature (T)	2	0.200	0.188	0.671
C. quitensis	Water Condition (WC)	2	394.8	333.4	**<0.001**
	T*WC	2	0.200	0.150	0.704
	Error	14	16.6		
	Temperature (T)	2	0.405	42.76	**<0.001**
D. antarctica	Water Condition (WC)	2	0.428	45.17	**<0.001**
	T*WC	2	0.238	25.10	**<0.001**
	Error	14	0.009		
	Temperature (T)	2	0.008	0.292	0.597
J. bufonius	Water Condition (WC)	2	0.406	13.381	**0.002**
	T*WC	2	0.003	0.111	0.744
	Error	14	0.034		
	Temperature (T)	2	0.205	13.482	**0.002**
P. annua	Water Condition (WC)	2	0.105	0.658	0.430
	T*WC	2	0.046	2.509	0.135
	Error	14	0.260		

Table 2
Two-way ANOVAs on the effects of temperature (6°C or 8°C) and water availability (LW or HW) on percentage of mortality of native (*C. quitensis* and *D. antarctica*) and non-native (*J. bufonius* and *P. annua*) Antarctic vascular plants

Biomass	**Factors**	**Df**	**SS**	***F***	***p***
	Temperature (T)	2	0.320	16.144	**0.001**
C. quitensis	Water Condition (WC)	2	0.034	1.717	0.211
	T*WC	2	0.006	0.315	0.583
	Error	14	0.019		
	Temperature (T)	2	0.544	24.550	**<0.001**
D. antarctica	Water Condition (WC)	2	0.029	1.323	0.269
	T*WC	2	0.005	0.263	0.615
	Error	14	0.031		
	Temperature (T)	2	0.293	5.920	**0.029**
J. bufonius	Water Condition (WC)	2	0.160	3.232	**0.043**
	T*WC	2	0.001	0.002	0.962
	Error	14	0.695		
	Temperature (T)	2	0.020	0.451	**0.050**
P. annua	Water Condition (WC)	2	0.023	0.526	0.480
	T*WC	2	0.006	0.141	0.713
	Error	14	0.621		

Competition Experiments (Experiment 2)

The presence of both non-native species had a significant effect on the accumulation of biomass for both native species (Table 3). The presence of non-native individuals (both species) and water availability significantly decreased the *C. quitensis* biomass, this decrease was more intense when the conditions were 6°C/LW (Table 3, Fig. 2a-d). The presence of *J. bufonius* individuals, the temperature and interaction of both factors had a significant effect on the *D. antarctica* accumulation of biomass. Especially at 6°C, the greatest decrease in biomass was recorded (Fig. 3a, b). Additionally, the presence of *P. annua* individuals and water availability and the interaction of these variables had a significant effect on the accumulation of biomass of *D. antarctica* (Table 3). Biomass production being the lowest at 6°C/LW (Fig. 3c, d).

Table 3

Three-ways ANOVAs on the effects of temperature, the water conditions, and non-native species competition (*P. annua* and *J. bufonius)* on biomass accumulation in native antarctic vascular plants *D. antarctica* and *C. quitensis*.

Factors	**Df**	**SS**	**F**	***p***
C. quitensis - J. bufonius				
Competition (C)	1	0.209	4.795	**0.033**
Temperature (T)	1	0.551	12.622	**<0.001**
Water condition (WC)	1	0.245	5.617	**0.021**
C: T	1	0.013	0.305	0.582
C: WC	1	0.008	0.019	0.890
T: WC	1	0.014	0.324	0.571
C: T: WC	1	0.008	0.183	0.670
Error	51	0.043		
C. quitensis - P. annua				
Competition (C)	1	0.054	2.427	**0.001**
Temperature (T)	1	0.214	9.501	**0.003**
Water condition (WC)	1	0.273	12.154	**0.001**
C: T	1	0.001	0.006	0.940
C: WC	1	0.304	13.507	**0.005**
T: WC	1	0.018	0.800	0.375
C: T: WC	1	0.012	0.555	0.459
Error	51	1.148		
D. antarctica - J. bufonius				
Competition (C)	1	1.156	61.188	**<0.001**
Temperature (T)	1	0.360	19.097	**<0.001**
Water condition (WC)	1	0.006	0.031	0.861
C: T	1	0.265	14.059	**<0.001**
C: WC	1	0.042	2.233	0.141
T: WC	1	0.043	2.323	0.133

Factors	Df	SS	F	*p*
C: T: WC	1	0.002	0.145	0.705
Error	51	0.963		
D. antarctica - P. annua				
Competition (C)	1	0,179	23.070	**<0.001**
Temperature (T)	1	0.040	5.203	**0.026**
Water condition (WC)	1	0.168	21.704	**<0.001**
C: T	1	0.004	0.602	0.441
C: WC	1	0.032	4.127	**0.041**
T: WC	1	0.002	0.379	0.540
C: T: WC	1	0.001	0.007	0.931
Error	51	0.395		

Mortality in *C. quitensis* individuals was influenced by the presence of *J. bufonius* individuals, temperature and water availability and the interaction of these factors (Table 4) The increase in the mortality of this species was observed, mainly at 6°C/LW, varying by 20-25% compared to the control (Fig. 4a, b). Regarding the interaction of *C. quitensis* and *P. annua*, it was observed that temperature and water availability and the interaction between the presence of non-native individuals and temperature had a significant effect on the mortality of *C. quitensis* individuals (Table 4, Fig. 4c, d). For *D. antarctica*, the presence of *J. bufonius* individuals, as well as the interaction between temperature and water availability, showed significant effects on the mortality of their individuals (Table 4), with increases ranging from 10 to 30% with the highest mortality at 6°C/HW (Fig. 5a, b). The same trend was observed in the presence of *P. annua* individuals, temperature and water availability had a significant effect on the mortality of *D. antarctica* (Table 4), where the mortality of *D. antarctica* was higher (27%) at 6°C/LW (Fig. 5c, d).

Table 4

Three-ways ANOVAs on the effects of temperature, the water conditions, and non-native species competition (*P. annua* and *J. bufonius)* on mortality in native antarctic vascular plants *D. antarctica* and *C. quitensis*.

Factors	**Df**	**SS**	**F**	***p***
C. quitensis - J. bufonius				
Competition (C)	1	4557	700.930	**<0.001**
Temperature (T)	1	303	46.630	**<0.001**
Water condition (WC)	1	646	99.319	**<0.001**
C: T	1	179	27.490	**<0.001**
C: WC	1	59	9.134	**0.003**
T: WC	1	6	0.898	0.347
C: T: WC	1	2	0.233	0.631
Error	51	332		
C. quitensis - P. annua				
Competition (C)	1	2718.9	365.237	**<0.001**
Temperature (T)	1	20.9	2.811	**0.049**
Water condition (WC)	1	998.3	134.113	**<0.001**
C: T	1	19.1	2.566	0.115
C: WC	1	10.9	1.460	0.232
T: WC	1	103.5	13.905	**<0.001**
C: T: WC	1	54.9	7.370	**<0.001**
Error	51	379.6		
D. antarctica - J. bufonius				
Competition (C)	1	4821	733.963	**<0.001**
Temperature (T)	1	1401	213.281	**<0.001**
Water condition (WC)	1	306	46.611	**<0.001**
C: T	1	719	109.399	**<0.001**
C: WC	1	178	27.149	**<0.001**
T: WC	1	13	2.033	0.160

Factors	Df	SS	F	*p*
C: T: WC	1	9	1.362	0.249
Error	51	328		
D. antarctica - P. annua				
Competition (C)	1	1243	4.511	**0.038**
Temperature (T)	1	22	0.080	0.779
Water condition (WC)	1	53	0.194	0.661
C: T	1	1404	5.094	**0.028**
C: WC	1	1288	4.674	**0.035**
T: WC	1	387	1.405	0.241
C: T: WC	1	1354	4.912	**0.031**
Error	51	14058		

Discussion

The results indicated that, except for *D. antarctica*, the increase in temperature had a significant effect on the biomass production of the species under study, this effect being more intense with greater water availability for *C. quitensis* and *J. bufonius*. For *D. antarctica* and *P. annua* an effect of water availability on biomass production was not observed. These results coincide with the general trends of the Eco-physiological response (photosynthetic performance) and growth (biomass accumulation) of native species. Several studies have determined that the increase in temperature above 7°C generates a significant increase in biomass production, modifying the relative growth rate, increasing photosynthetic performance, and decreasing the mortality percentage in *C. quitensis* (Day et al. 1999; Torres-Díaz et al. 2016; Acuña-Rodriguez et al. 2017; Fuentes-Lillo et al. 2017a). In *D. antarctica* biomass accumulation decreases with an improvement of temperature and water availability has been observed. Additionally, our results highlight the importance of the increase in water availability (about ~30% increase) on the general performance of *C. quitensis*. Water availability has been determining as one of the most significant variables for increases in the accumulation of biomass and the photosynthetic performance of native Antarctic species (Molina-Montenegro et al. 2012; Torrez-Diaz et al. 2016; Fuentes-Lillo et al. 2017a).

Concerning non-native species, our results coincide with previously published studies, where biomass production and the photosynthetic response of *J. bufonius* increase significantly as a function of the joint effect of increased temperature and water availability (Fuentes-Lillo et al. 2017a). These results have been supported by Cavieres et al. (2018) studies, where the increase in temperature to 11°C favored the accumulation of biomass for non-native species. Moreover, we determined that water availability does not influence the biomass production of *P. annua*. But the results obtained by Molina-Montenegro et al. (2019) have been shown that an increase in water availability (over ~25% at current conditions in Antarctica) is the most important variable to explain the increase in biomass production of *P. annua.* The higher biomass production associated with climate change found in both native and non-native species was related to a higher net photosynthesis rate that occurs due to increased temperature (Xiong et al. 1999, 2000; Dusenge et al. 2019). Likewise, it has been determined that in ecosystems with extreme climates the joint effect of temperature and precipitation significantly increases the primary production of herbaceous plants and grasses (Ma et al. 2017). Our results support the general patterns that indicate that there are no differential responses between native and non-native species to the effect of climate change (Sorte et al. 2013). Therefore, we could expect that both native species, mainly *C. quitensis*, and both non-native species analyzed in this study could increase their distribution ranges and colonize ice-free area in the Antarctic Peninsula along with improvement of environmental conditions (Chen et al. 2011; Lee et al. 2017).

Under this context, it has been determined through *in situ* monitoring that the effect of global warming has had implications on the increase in abundance, cover, and changes in the distribution range of *C. quitensis* and *D. antarctica* (Smith 1994; Grobe et al. 1997; Torres-Mellado et al. 2011; Canone et al. 2016). Our results indicate that *D. antarctica* is not favored by the effect of climate change in terms of its biomass accumulation, although Torres-Mellado et al. (2011) *in situ* studies have shown that there is an increase in coverage (~20%) associated with the increase in temperature experienced in the Antarctic Peninsula. Different distribution models have determined that non-native species such as *P. annua*, because of climate change and increased anthropogenic pressure, could significantly increase their distribution area in the Antarctic Peninsula (Pertierra et al. 2017; Dutty et al. 2017). While, for *J. bufonius*, there are no distribution models that explain how climate change could affect the species distribution in this region. But some studies have evaluated, through distribution models, a significant expansion of the distribution area of *J. bufonius* on sub-Antarctic islands where its probability of occurrence increases when the mean temperature exceeds 4°C (Bazzichetto et al. 2020).

Although climate change could benefit the range pattern of native and non-native species. This range increase could have implications on future interactions among native and non-native species, such as an increase in competition among them (Corlett and Westcott 2013; Lancaster et al. 2017), as the observations of Molina-Montenegro et al. (2016, 2019) have been already shown.

Competition Experiment

It has been determined that the synergy between climate change and the intensity of the interaction between native and non-native species in different ecosystems are context dependent and species specific (Diez et al 2012; Sorte et al. 2013; Dainese et al. 2017; Zettlemoyer et al. 2019). Under this context, our results support these conclusions that the biomass production of *C. quitensis* is reduced in the presence of both non-native plants, but no great differences are seen if this interaction occurs under current conditions (LW/6°C) and "climate change" conditions (HW/8°C), when compared with control. This reduction in biomass in the presence of non-native species resulted in a significant increase in the mortality of *C. quitensis*. The RII interaction between *C. quitensis/J. bufonius* and *C. quitensis/P. annua* indicates that when water availability is the limiting factor (LW) at 6°C, the predominant interaction is competition, but if water availability increases the presence of *J. bufonius* generates a competitive interaction at 8°C, while in the interaction *C. quitensis/P. annua* predominates is facilitation, independent of temperature.

Our results agree with experimental field studies where the presence of individuals of *P. annua*, at the water increased availability (-20 Kpa), affected the biomass accumulation in individuals of *C. quitensis* and *D. antarctica*. This research also indicates an asymmetric competition between these species, favoring the growth and survival of the *P. annua* (Molina-Montenegro et al. 2016, 2019).

Our results indicated that under current and future conditions of water availability there could be a competitive effect of *P. annua* on both native species, which are mainly associated with the hydric conditions used in this study, which differ from the conditions used in other studies (Molina-Montenegro et al. 2016; 2019).These results confirm that the expansion of the distribution range of *P. annua* in the Antarctic ecosystem would result in a decrease in the growth of native species (Molina-Montenegro et al. 2012, 2015, 2016, 2019).

However, it is important to take these results with caution, since there are other types of abiotic variables that can influence the competitive interactions between *C. quitensis* and *P. annua*. Studies by Cavieres et al. (2018) point out the presence of a certain type of resistance of part of *C. quitensis* individuals to *P. annua* at 5 and 11°C and two nitrogen concentrations. No previous studies have evaluated *J. bufonius* competitive effect, but we observe this species grows without difficulty under current and "climate change" conditions and generates a competitive effect on native species. We could expect its response to be like that of *P. annua*, whereby expanding its range of distribution in Antarctic ecosystems generates a decrease in biomass production in native species, mainly if there is a continuous increase in water availability in Antarctic ecosystems.

The presence of the non-native species *J. bufonius* and *P. annua* reduce the biomass of *D. antarctica* both current conditions and of future climate change compared to the species growing without non-native species, generating a significant increase in mortality (over ~30%) of individuals of *D. antarctica*. The RII indicated that the presence of *J. bufonius* generates competition in both conditions of water availability, being more intense at 8°C, while the presence of *P. annua* competition to LW is more intense at 6°C, while at HW is strongest at 8°C. Our results agree with the results obtained in previous studies where it has been indicated that *D. antarctica* is more susceptible to the presence of *P. annua* individuals associated with both an increase in water availability and temperature (Molina-Montenegro et al. 2016), the density of individuals of *P. annua* (Molina-Montenegro et al. 2012, 2019) as under a decrease in the nitrogen content in the soil (Cavieres et al. 2018).

This greater susceptibility of *D. antarctica* may be associated with the phylogenetic and functional similarities between *D. antarctica* and both non-native species. Various studies have determined that ecological, phylogenetic, and even functional traits similarities tend to make competition for resources more intense (Cahill et al. 2008; Dostal et al. 2011; Burns and Strauss 2012; Kunstler et al. 2012). Additionally, these results agree with previous conclusions that indicate that *D. antarctica* could be the species most susceptible to the expansion of *P. annua* and to other non-native species that could arrive and invade Antarctic Peninsula (Molina-Montenegro et al. 2012; 2016, 2019).

Final Remarks

Currently, abiotic conditions and low anthropogenic pressure are two of the most important variables that explain the low abundance of non-native species in Antarctic ecosystems, however, the global change process (increased temperature and greater anthropogenic pressure) will increase mean the presence of non-native species, mainly in the Antarctic Peninsula (Dutty et al. 2017; Hughes et al. 2020). Several studies have registered an important pool of seeds of non-native species that are transported by human activities (Chown et al. 2012; Huiskes et al. 2014) and there is even a percentage of seeds of non-native species that have been found in soils associated with human activities (within these species some seeds of the genus *Juncus sp*) (Fuentes-Lillo et al. 2017a). Germination studies that include 16 species of different growth forms, determined that there is a large percentage of these non-native species that could germinate and even grow under the current abiotic conditions that prevail in the Antarctic Peninsula (Bokhorst et al. 2021). Therefore, our results (mainly the influence of *J. bufonius*) could give an approximation about what would be the competitive response of non-native species that could be arriving at the Antarctic Peninsula.

Performing more studies that evaluate the possible interactions between possible non-native species (species with more problems arriving on the peninsula i.e., Hughes et al. 2020) and native Antarctic species would help to evaluate the possible impacts that these new species generate on the native flora, giving the possibility of focusing efforts on preventing the arrival of the most problematic non-native species.

The most invasive species can rapidly dominate and change the abundance of native species in a community (Colautti and MacIsaac 2004) interacting strongly with the resident (Gurevitch and Padilla 2004; Sax and Gaines 2008). Thus, invasive species like *P. annua* and *J. bufonius* may establish in natural Antarctic communities, but to remain community dominants, the competitive advantage of invasive species must be persistent. The question is if native species have the demographic and genetic resources necessary to evolve in response to the non-native invader before going locally extinct or limit their populations. Molecular data revealed evident genetic structure within *C. quitensis* populations from South America and Antarctica with the lowest genetic diversity in Antarctic populations. Moreover, similar results were obtained for *D. antarctica*. The gene pool subdivision, as well as relatively low genetic diversity found in the Antarctic populations of both species, suggest that the species may have survived the Last Glacial Maximum in refugia located on isolated islands of the Maritime Antarctic. Moreover, those results point to limited gene flow between populations from those two regions (Chwedorzewska and Bednarek 2008; Androsiuk et al. 2018). So, the question is still open if the population sizes and genetic diversity of native species are large enough, if yes, native species may be able to evolve traits that allow them to co-occur with invasive species or even evolve to become effective competitors with invasive species. But also, demographic factors such as population size and growth rates, as well as the number of factors including gene flow, genetic drift, the number of selection agents, encounter rates, and genetic diversity may affect the invasive species (Leger and Espeland 2009). As show by Wódkiewicz et al. (2019) studies, in the populations of *P. annua* along with the dispersion process decreased genetic variability.

Management efforts that reduce the population size and genetic diversity of invasive species can reduce the ability of those species to compete. Also, human activities affect gene flow within invasive species by continual reintroduction either from the native range or from other invasive populations can be a significant source of genetic diversity within invasive populations (Ellstrand and Schierenbeck 2000; Sexton et al. 2002). Keeping the genetic diversity of invasive populations low may limit their evolutionary potential. Secondly, creating barriers between invasive populations, in the form of breaks between patches, could limit gene flow and keep the effective population sizes smaller, increasing the likelihood of genetic drift and preventing the maintenance of incurred genetic diversity.

Declarations

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Not applicable

Authors' contributions

Research design and acquisition of data by MCD and EFL, Data analysis by EFL, Interpretation of data and manuscript drafting and editing by MCD, EFL and KJC.

Statements & Declarations

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Figures

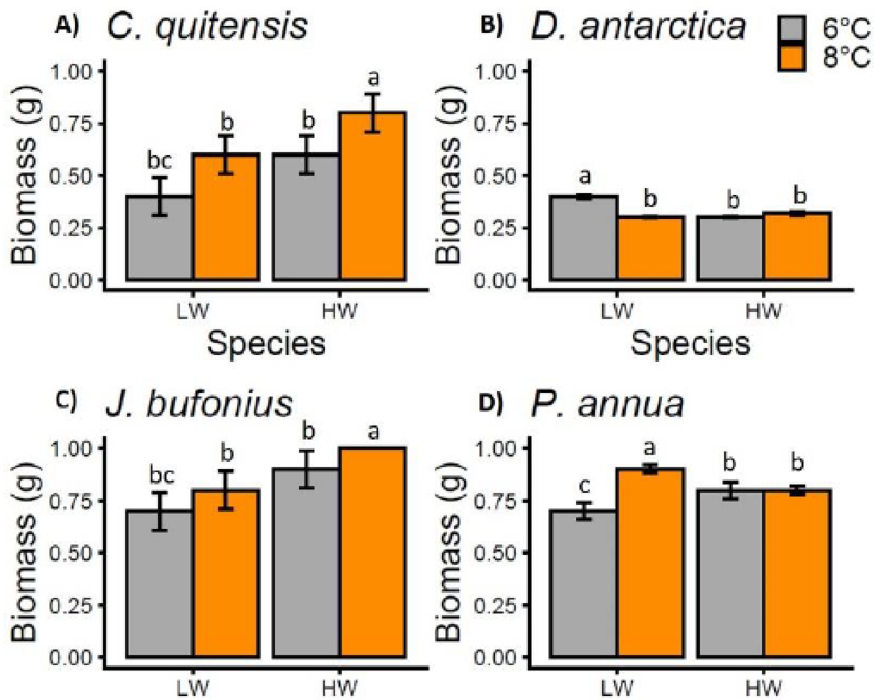

Figure 1. Biomass accumulation of native (*C. quitensis* and *D. antarctica*) and non-native (*J. bufonius* and *P. annua*) Antarctic vascular plants under different conditions of temperature (6°C-grey and 8°C-orange) and water availability (Low-LW and high- HW). Different letters show significant differences with a p value <0.001.

Figure 1

See image above for figure legend.

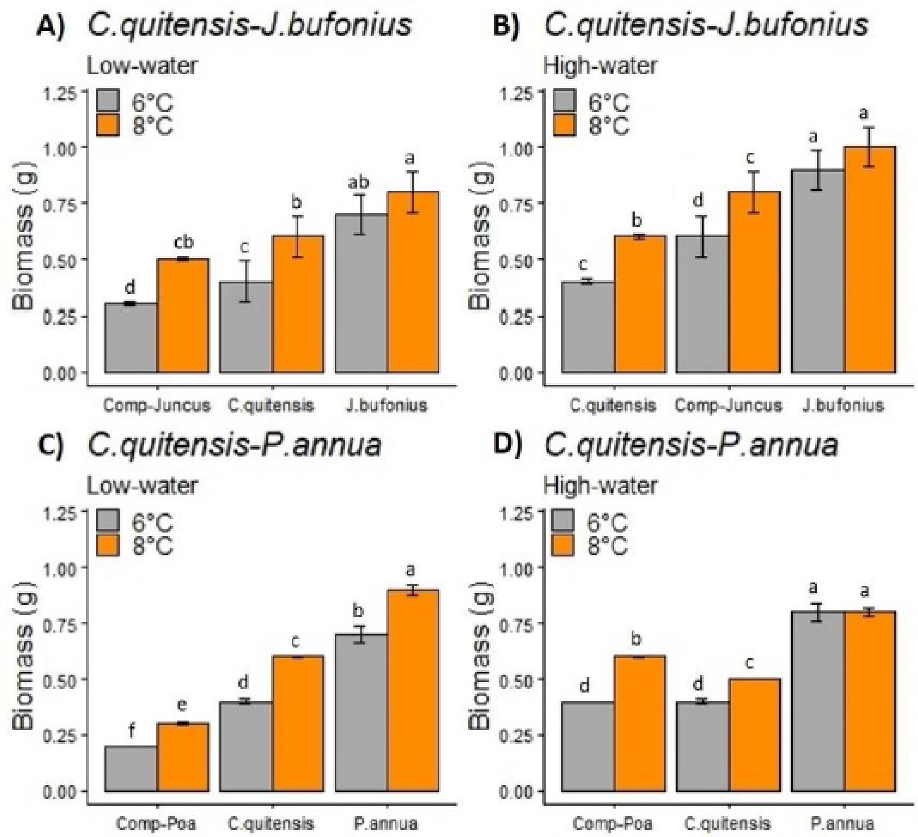

Figure 2. Biomass accumulation of *C. quitensis* under different temperature conditions (6°C-grey and 8°C-orange) and water availability (Low-LW and high- HW), and in presence of non-native species *J. bufonius* (A and B) and *P. annua* (C and D). Different letters show significant differences with a p value <0.001.

Figure 2

See image above for figure legend.

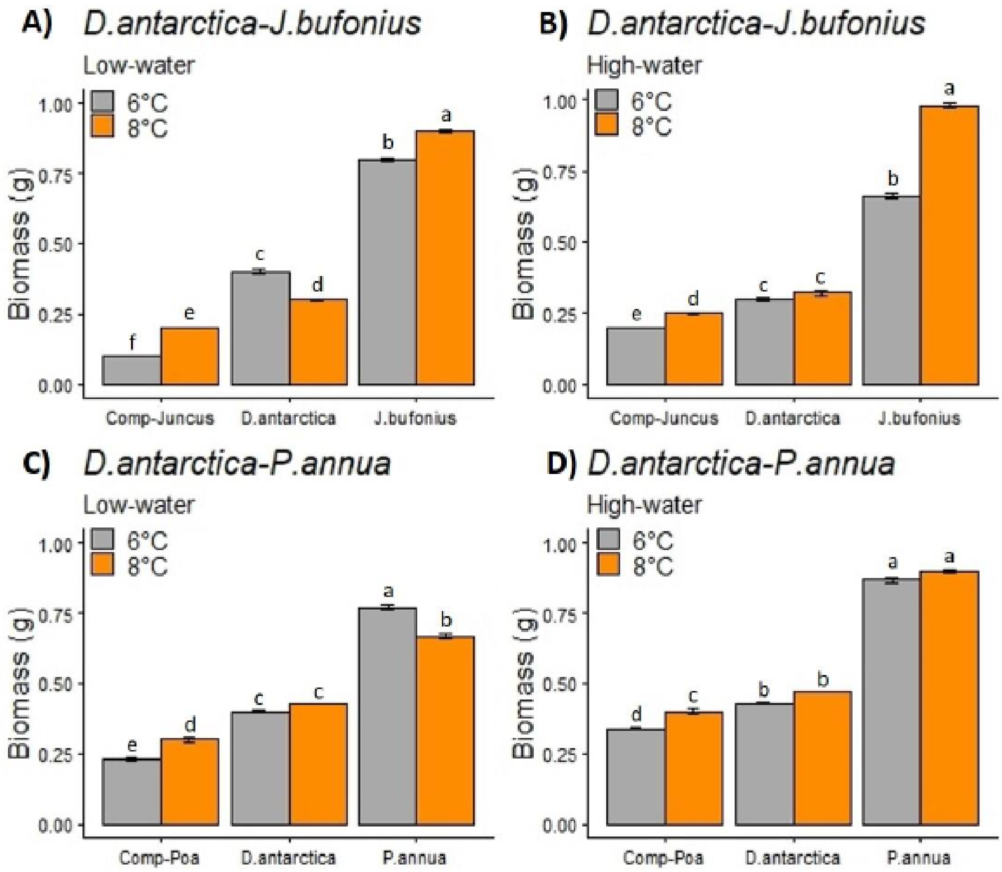

Figure 3. Biomass accumulation of *D. antarctica* under different temperature conditions (6°C-grey and 8°C-orange) and water availability (Low-LW and high- HW), and in presence of non-native species ***J. bufonius*** (A and B) and ***P. annua*** (C and D). Different letters show significant differences with a p value <0.001.

Figure 3

See image above for figure legend.

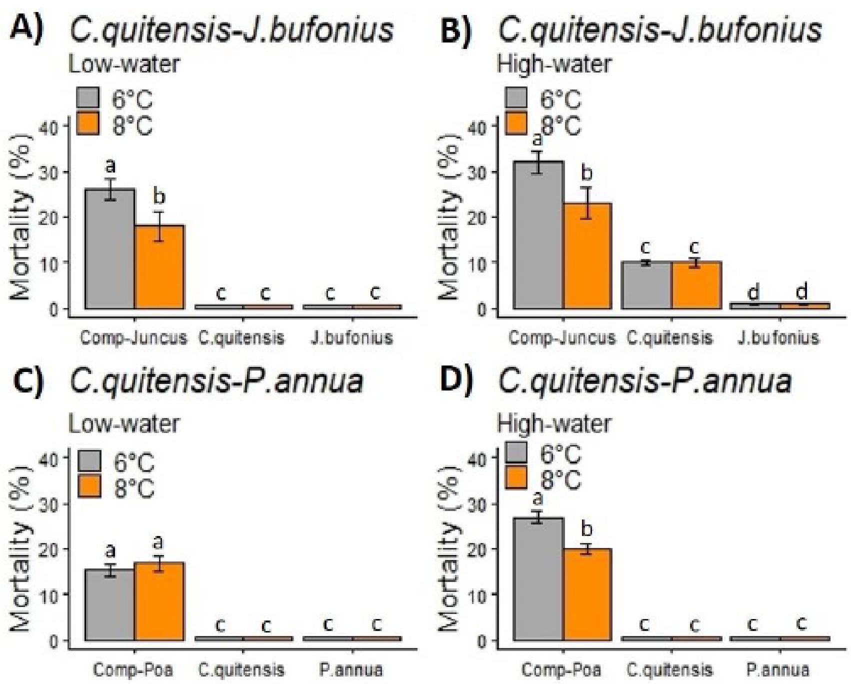

Figure 4. Percentage of mortality accumulation in *C. quitensis* under different temperature conditions (6°C-grey and 8°C-orange) and water availability (Low-LW and high- HW), and in presence of non-native species *J. bufonius* (A and B) and *P. annua* (C and D). Different letters show significant differences with a p value <0.001.

Figure 4

See image above for figure legend.

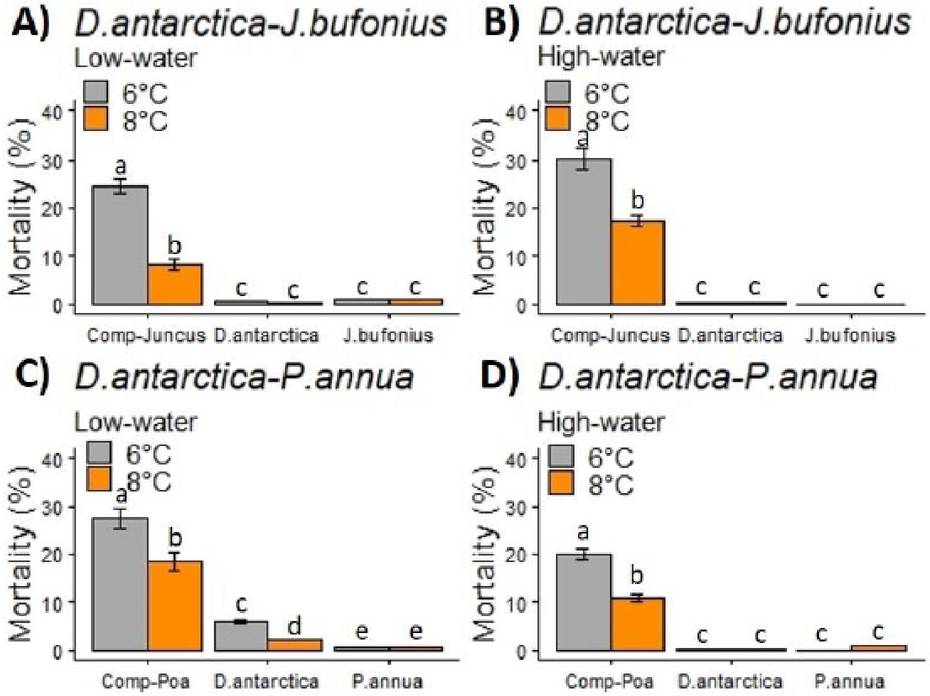

Figure 5 Percentage of mortality in *D. antarctica* under different temperature conditions (6°C-grey and 8°C-orange) and water availability (Low-LW and high- HW), and in presence of non-native species *J. bufonius* (A and B) and *P. annua* (C and D). Different letters show significant differences with a p value <0.001.

Figure 5

See image above for figure legend.

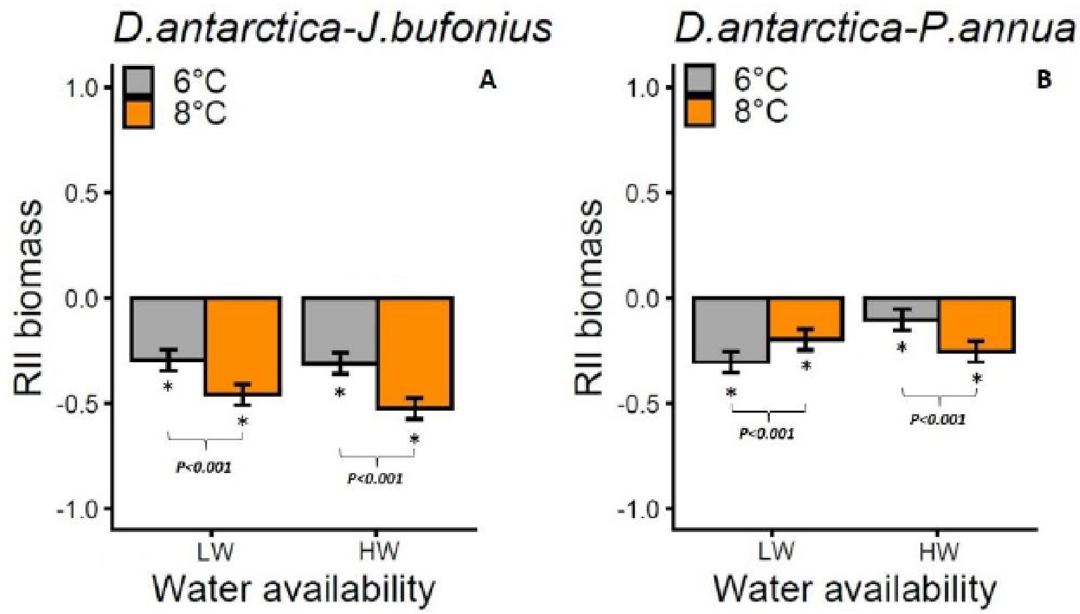

Figure 6. Relative interaction index (RII) of the biomass in *C. quitensis* in presence of individuals of the non-native species *J. bufonius* (A) and *P. annua* (B). The asterisks are the result of the t-test, indicating significant differences depending on whether they are different from 0, while the p-values show significant differences between temperatures (6 ° C and 8 ° C).

Figure 6

See image above for figure legend.

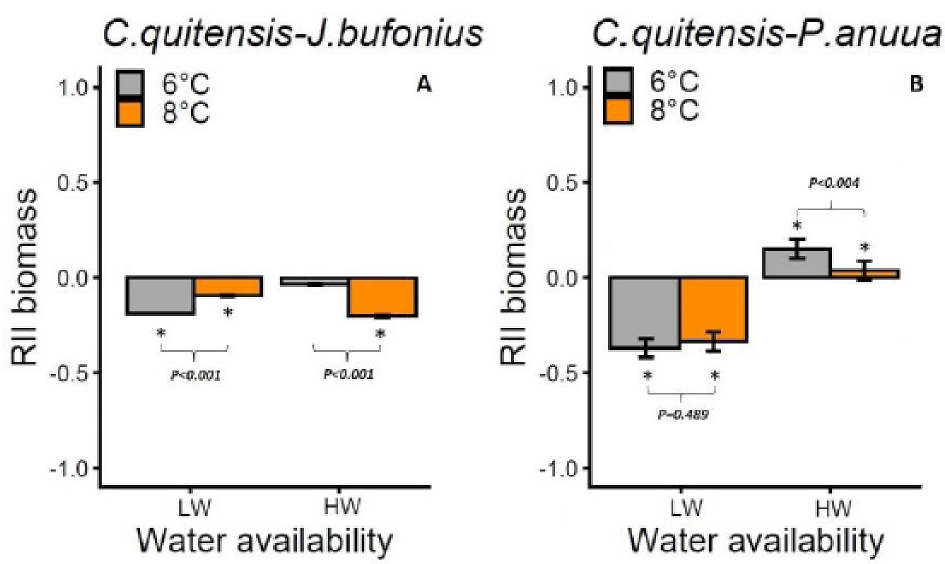

Figure 7. Relative interaction index (RII) of the biomass in *D. antarctica* in presence of individuals of the non-native species *J. bufonius* (A) and *P. annua* (B). The asterisks are the result of the t-test, indicating significant differences depending on whether they are different from 0, while the p-values show significant differences between temperatures (6 ° C and 8 ° C).

Figure 7

See image above for figure legend.

Supplementary Files

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