



# Predicting distributional shifts of commercially important seaweed species in the Subantarctic tip of South America under future environmental changes

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## Abstract

Shifts in species distributions are among the observed consequences of climate change, forcing species to follow suitable environmental conditions. Using species distribution models (SDMs), we aimed at predicting trends in habitat shifts of two seaweed species of commercial interest in the Subantarctic Patagonian region in response to ongoing environmental changes across temperate South America and worldwide. We gathered occurrence data from direct, on-site visual, and taxonomic identification (2009–2018) from global databases of species occurrence and from the scientific literature. We built the SDMs selecting putative predictors of biological relevance to *Lessonia flavicans* and *Gigartina skottsbergii*. We calibrated the SDMs using MaxEnt and GLMs for model evaluation, splitting our occurrence datasets into two parts: for model training and for model testing. The models were projected to future climate change scenarios (Representative Concentration Pathway: RCP 2.6 and RCP 8.5) to examine trends in shifting habitat suitability for each species. Maximum sea surface temperature was the main predictor variable, followed by minimum nitrate concentration, explaining both species' distributional shift across Subantarctic shorelines by the year 2050. Projection of the SDM for each species under altered environmental conditions to 30–40 years into the future resulted in a south poleward shift with a reduction in habitat range for both species. Such responses would threaten their persistence, local marine species richness, biodiversity, ecological function, and thereby, the commercial and ecosystem services provided by *L. flavicans* and *G. skottsbergii* in Subantarctic South America.

**Keywords** Species distribution models (SDM) · Marine habitat niches · Warming temperatures · Nutrient concentrations

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## Introduction

As the planet warmed after the Last Glacial Maxima (23,000–17,000 years ago), species distributions shifted to higher latitudes or higher elevations (Davis and Shaw 2001). Under current climate warming globally, these distributional trends continue for many species (Parmesan et al. 1999; Parmesan and Yohe 2003, VanDerWal et al. 2013; Fraser 2016). Marine species, in particular, are shifting their latitudinal (e.g., Parmesan 2006) and/or depth ranges (Dulvy et al. 2008) as climate change continues to alter their habitats (e.g., temperature, sea level, dissolved O<sub>2</sub>), and thereby, the organisms' physiologies, phenologies, fitness, and species interactions (Parmesan and Yohe 2003; VanDerWal et al. 2013; IPCC 2014; Franco et al. 2018). The shifting niches of marine species in response to ocean warming may alter community composition and local richness patterns, leading to local extinctions and/or invasions (Cheung et al. 2009) and thus change marine trophic webs. Seaweeds, for instance, are paramount

components of marine systems as primary producers and ecosystem engineers. In coastal environments, recent shifts in seaweed distributions, and those of their associated organisms, are reportedly linked to rising temperatures due to climate change (Fraser et al. 2009, 2012; Nikula et al. 2010; Wernberg et al. 2011; Martínez et al. 2018).

Altering seaweed richness and biodiversity can have negative effects on ecosystem function (e.g., CO<sub>2</sub> sequestration; Barbier et al. 2011) on local fisheries (Cheung et al. 2009; Fraser et al. 2009; Nikula et al. 2010; Fraser et al. 2012) and on marine resources of commercial interest (Ojeda et al. 2018). Seaweeds are vital to food webs in both shallow and deep waters. They support shallow waters providing structural habitat to biodiverse vertebrates and invertebrates (Wiencke and Amsler 2012; Quartino et al. 2013) and provide nutritional energy to higher trophic levels, supporting deep waters via detrital export to benthic food chains (Wiencke and Amsler 2012). Seaweeds are also becoming increasingly important for human societies as food sources, pharmaceutical aids, and for medical purposes (Cardoso et al. 2014; Anis et al. 2017). Especially in many subpolar regions, coastal communities have been using seaweeds for multiple purposes for centuries (Sudha 2017; Ojeda et al. 2018) and they are of crucial socio-economic, cultural, and ecological importance there (Wiencke and Amsler 2012). However, rising ocean temperatures and coastal ice melt in subpolar latitudes are affecting seaweed distributions, community composition, and the goods and services they provide more than in other regions of the globe (Turra et al. 2013).

Given their importance, the potential impacts of climate change on subpolar, coastal seaweed ecosystems are a major focus of concern (Harley et al. 2006), especially in high-latitude ice-receding habitats. Data to predict the distribution of species and habitat shifts are key to biodiversity analyses and biocultural conservation. But identifying the set of factors that may determine future species occurrence and spatiotemporal dynamics under variable habitat conditions is complex (Brown and Knowles 2012), as it must consider covarying abiotic and biotic factors and their interactions in the environment (Phillips et al. 2006; Franco et al. 2018). Furthermore, the factors determining species occurrence and distribution are scale-dependent (Austin and Van Niel 2011) and often linked with ecosystem processes. Knowledge of both the realized and potential distribution (niche) of seaweed species is essential to assess their vulnerability to potential global changes (e.g., Turra et al. 2013).

Species distribution models (SDMs) have become increasingly applicable in conservation, as well as in management of natural resources (Evans et al. 2016; Franco et al. 2018; Sofaer et al. 2018). For species of commercial interest, in particular, combining current occurrence records and suitable habitat data has much potential to create models to predict the possible changes in distribution under future conditions (Evans et al.

2016; Sofaer et al. 2018). As ocean temperatures rise, non-migratory marine species unable to move to new suitable habitats (e.g., higher latitude) may become locally or totally extinct, or significantly reduce their range distribution (Thomas et al. 2004). Sedentary benthic species, such as seaweeds and some invertebrates, may only colonize newly opened habitat niches at spore stages of their life history (Muth et al. 2019). But polar and subpolar environmental conditions may not be favorable for many algal fragile stages to settle in newly opened subtidal sites if disturbance from ice scour, ice-melt, and reduced light penetration in the water column (turbidity, sedimentation; Quartino et al. 2013) ensue rising temperatures. Hence, phenology, recruitment physiology (Fraser 2016; Muth et al. 2019), and photosynthetic performance of Subantarctic seaweeds might also limit their potential to follow shifting habitat suitability due to warming climate and related disturbances (Quartino et al. 2013). Alternately, recent phylogeographic studies suggest long-distance rafting “migration” of seaweeds is indeed favored at high latitudes (50°–60°; Tala et al. 2019), But these also depend on season (temperature, irradiance, nutrients) and species persistence, physiological acclimation and morphological damage (e.g., proportion of mature reproductive structures) during long drift times (Batista et al. 2018; Tala et al. 2019). Local extinction or shrunk range distribution of important Subantarctic seaweeds would affect local marine trophic interactions and ecosystem function. Modeling approaches, such as SDMs can help us predict how keystone algae species may respond to subsequent global warming, and which species may be capable of enduring novel environmental conditions under rising temperatures.

Subantarctic Chile is one of the world’s fastest warming regions according to oceanographic data (Cavan and Boyd 2018; Moore et al. 2018), glacier records, and tree-ring chronologies (Lara et al. 2005; Iriarte 2018). Stronger research efforts must be invested to document environmental alterations in its coastal systems, to predict future changes and to evaluate potential biotic responses to such predictions (e.g., Convey and Peck 2019). Coastal subpolar systems are transition zones where species may already live close to their physiological thresholds and zones particularly sensitive to rapid regional climate change (IPCC 2014; Iriarte 2018). Especially in Subantarctic Chile, *Lessonia flavicans* Bory (Searles 1978) and *Gigartina skottsbergii* Setchell et Gardner (Setchell and Gardner 1936) are socio-economically and biologically key to support the unique ecosystems of the Cape Horn Biosphere Reserve (Miloslavich et al. 2011; Rozzi et al. 2012) and the coastal communities of the Patagonian archipelago (e.g., Iriarte 2018; Ojeda et al. 2018). The growing importance of marine seaweeds to support human societies globally and their ancient significance in many Asian and developing countries intensifies interest in creating models to predict the effects of climate change on such vital organisms (Wernberg et al. 2011;

Tyberghein et al. 2012; Verbruggen et al. 2013; Martínez et al. 2018). In the present study, our goal was to predict potential distributional shifts of two commercially important species of seaweeds in Chile's Subantarctic Region, *L. flavicans* and *G. skottsbergii*, in response to ongoing environmental changes. Using SDM approaches, our specific objectives were to project the models for each algae species to future (year 2050) climate change scenarios (Representative Concentration Pathway: RCP 2.6 and RCP 8.5) to identify their habitat suitability shifting trends across shorelines of the subpolar tip of South America.

## Materials and methods

We gathered occurrence data for *Lessonia flavicans* and *Gigartina skottsbergii* from a total of 216 sites in coastal Subantarctic Patagonia (Chile-Argentina) by combined direct and virtual approaches. Direct, on-site visual and taxonomic identification (2009–2018) were used to evaluate the presence of both macroalgae species. We used 10 transects per site, perpendicular to the coastline (0–10 m depth) and each transect was about 25 m apart from the next. Two observers walked along each transect recording the species present. Additionally, to build the SDMs, we gathered data of species-occurrence by performing searches on “*L. flavicans*” and “*G. skottsbergii*” in the scientific literature (e.g., AlgaeBase, Web of Science, Web of Knowledge, ScienceDirect), as well as the Global Biodiversity Information Facility (GBIF) and local sources (e.g., books, atlas, dissertations, and theses). Data were checked to remove duplicate and incorrect records (e.g., terrestrial occurrences). After this correction, we used the software Occurrence Thinner (Verbruggen et al. 2013) to reduce the effect of sampling bias in our data (Phillips et al. 2009).

We used environmental layers from Bio-Oracle 2 (BO; Assis et al. 2017), which is a set of geophysical, biotic, and climate data (e.g., current velocity, nitrate, temperature) for the world's oceans in a 5 arcmin spatial resolution. We cropped our rasters to the Subantarctic study province (Spalding et al. 2007; BO's “equal-area projection”; Assis et al. 2018) to a depth of 50 m, representing the geographical area encompassing the distribution of our focal species. This was used to estimate the niche requirements of the modeled species. We followed Rissler and Apodaca (2007) to avoid overparameterization and multi-collinearity of environmental variables. A correlation matrix was built considering all variables selected a priori following relevant criteria to seaweed eco-physiology (Austin 2002). Relevant predictors representing water motion, salinity, light, nutrients, and temperature were maximum current velocity, minimum cloud cover, mean nitrate, and mean phosphate, concentrations, minimum salinity, and maximum and minimum sea surface temperatures. We

modeled species living from the intertidal zone down to a 50-m depth, thus we used all “surface” variables. We then identified highly correlated ones ( $r > 0.9$ ) and excluded one of them according to their biological relevance. We built another correlation matrix and repeated the procedure until all variables kept in the model had correlations  $< 0.9$ . The set of predictor variables were then current velocity ( $\text{m s}^{-1}$ ), minimum surface nitrate concentration  $\mu\text{mol m}^{-3}$ , minimum surface salinity (PSS) and maximum surface temperature ( $^{\circ}\text{C}$ ). We performed data manipulation in raster package (Hijmans 2019) and correlation analysis on R version 3.5.1 (R Core Team 2018).

We used MaxEnt to generate the SDMs for *L. flavicans* and *G. skottsbergii*. MaxEnt offers a good predictive performance for presence-only data (Elith et al. 2006; Merow et al. 2013). Models were built using linear, quadratic, product, and hinge features in MaxEnt according to the number of unique records for each species (Phillips and Dudík 2008). Initially, MaxEnt models were fitted for each species using their full occurrence data and all available predictors. We then excluded variables that were not selected by MaxEnt (i.e.,  $< 5\%$  contribution) to select the variables to fit the final model for each species. Through this procedure, we used the most parsimonious models according to the biology of the modeled species (Austin 2002; Austin and Van Niel 2011). Model validation was performed based on 100 replicated runs of partitioned occurrence data using 80% for training the model and 20% for testing it. Accuracy was evaluated based on one threshold-independent measure, the area under the (receiver operating characteristic) curve (AUC; Fielding and Bell 1997) and one threshold-dependent measure. We calculated the true skill statistics (TSS; Allouche et al. 2006) using the equal training sensitivity and specificity MaxEnt threshold (i.e., same chance of correctly predicting positive and negative observations). Values above the threshold are presences and those below are absences. An AUC value of  $\leq 0.5$  indicates a model no better than random and a value of 1 indicates a model presenting perfect discrimination (Fielding and Bell 1997). TSS values varied from  $-1$  to 1. The values below 0 represent predictions no better than random and 1 represents perfect predictions (Allouche et al. 2006). Final models were produced for each species using 100% of the occurrences to build the predictions.

We projected our final models on to future environmental conditions, obtained from the 5th Coupled Model Intercomparison Project (CMIP5) of the Intergovernmental Panel on Climate Change (IPCC), to predict likely distributional shifts of *L. flavicans* and *G. skottsbergii* by 2050. Such climate change conditions follow a scenario of representative concentration pathway (RCP) 2.6 and a scenario of RCP 8.5 (IPCC 2014). The RCP 2.6 scenario is more optimistic, with the increase in atmospheric  $\text{CO}_2$  concentration reaching  $\sim 490$  ppm before 2100 (van Vuuren et al. 2011) and decreasing

with mean temperature increases of 0.3 to 1.7 °C (Collins et al. 2013). The RCP 8.5 predicts an increase in atmospheric CO<sub>2</sub> concentration reaching ~ 1370 ppm (van Vuuren et al. 2011) and continuing to increase with mean temperature increases of 2.6 to 4.8 °C (Collins et al. 2013) by 2100. Both scenarios' predictions were obtained from Bio-ORACLE2 (Assis et al. 2017). They were produced by averaging data from three distinct CMIP5 models: the CCSM4—Community Climate System Model 4, the HadGEM2-ES—Hadley Centre Global Environmental Model 2 (Earth System), and MIROC5—Model for Interdisciplinary Research on Climate 5 (Assis et al. 2017).

We transformed our models into binary rasters of presence-absence based on habitat suitability using the equal training sensitivity and specificity MaxEnt threshold. We estimated the projected habitat loss for *L. flavicans* and *G. skottsbergii*, as the displacement or shift, measured in degrees latitude, based on their current distributions and those under RCP 2.6 and RCP 8.5 along the coast of Subantarctic South America.

## Results

Our onsite, literature, and database searches, followed by cleaning of gathered data to remove sampling bias, yielded a dataset of 91 unique localities with *L. flavicans* present and a dataset of 168 unique localities with *G. skottsbergii* present in the Subantarctic tip of South America. These records yielded models with fair performance for both species, *L. flavicans* (AUC = 0.93 ± 0.01, TSS = 0.68 ± 0.05) and *G. skottsbergii* (AUC = 0.84 ± 0.01, TSS = 0.44 ± 0.06). Regardless of the geographical distribution of the modeled species, maximum sea surface temperature was the main predictor variable, followed by minimum nitrate concentration, presenting the highest gain contribution and being selected for both species' models of their projected distribution by the year 2050 (Table 1). Current velocity and minimum PSS showed no gain contribution to either *L. flavicans*' or *G. skottsbergii*'s projected distribution models.

**Table 1** Mean and standard deviation of the predictor variable's contribution to model projections on climate-induced shifts in range distribution of two biologically and commercially important seaweed species in Subantarctic South America: *Lessonia flavicans* and *Gigartina skottsbergii*. Shown are the number of samples for training/

	Validation models	Final models							
	Min surface nitrate	Max surface temperature	Training samples	Testing samples	Training AUC	Testing AUC	TSS	Training AUC	TSS
<i>Gigartina skottsbergii</i>	12.5 (± 1.0)	87.5 (± 1.0)	133	33	0.84 (± 0.01)	0.82 (± 0.03)	0.44 (± 0.07)	0.84	0.49
<i>Lessonia flavicans</i>	24.5 (± 4.9)	75.5 (± 4.9)	72	18	0.94 (± 0.00)	0.93 (± 0.02)	0.70 (± 0.05)	0.93	0.68

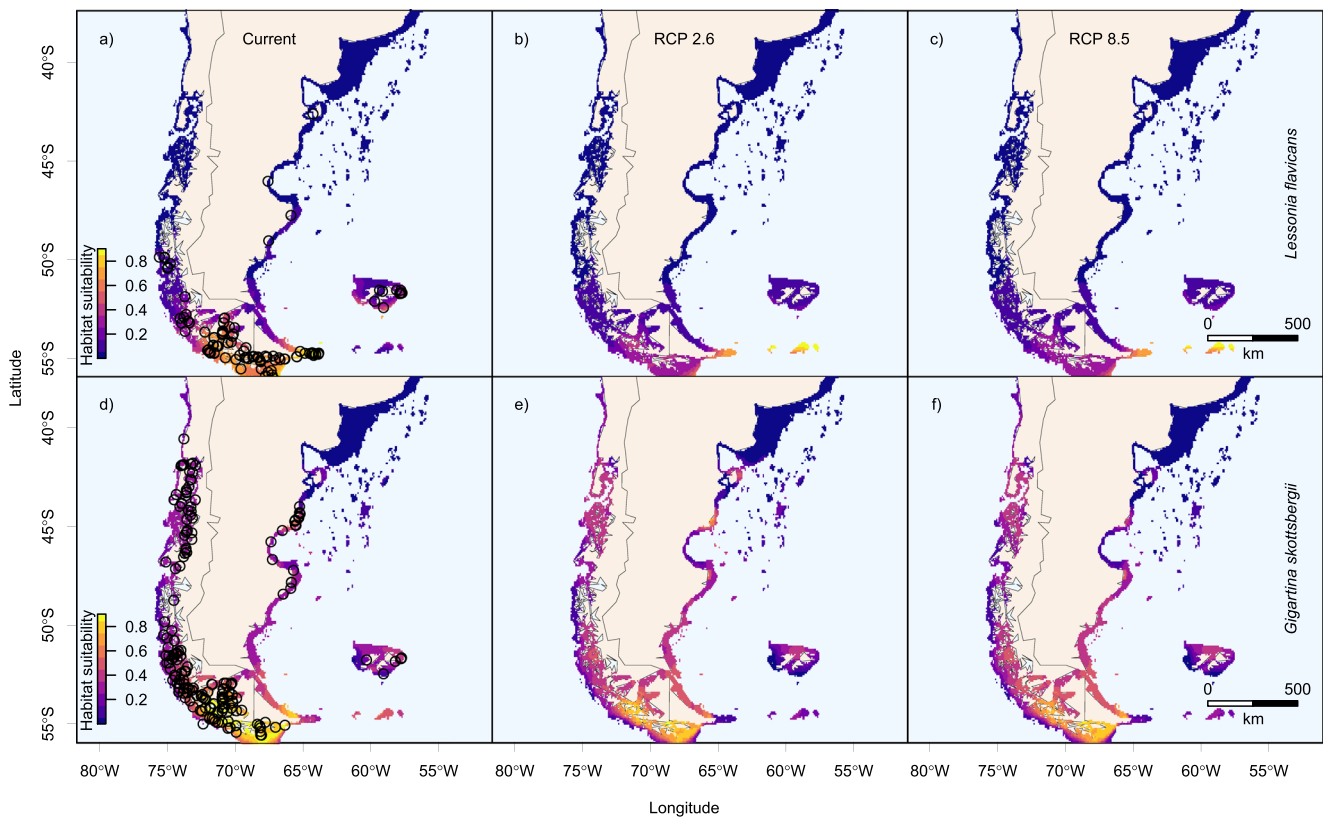
The projected habitat suitability presented a fair agreement with the known current distribution of both seaweed species across the Subantarctic shorelines of South America (Fig. 1). Model projections under future climate conditions (RCP 8.5 and RCP 2.6) show notable shifts in distribution, with higher habitat suitability "scores" (yellow, orange in Fig. 1) shifting south poleward for both species, and slightly eastward (*L. flavicans*). Important range reductions are predicted for these commercially important species by 2050 (Figs. 1 and 2).

Binary presence-absence maps for *L. flavicans* and *G. skottsbergii*, based on the equal training sensitivity and specificity threshold, show a decrease in the overall distributional area for both species upon contrasting current versus projected range distribution (Fig. 2). At RCP 2.6, the reduction in occurrence and persistence probabilities was similar for *L. flavicans* (presence reduced by 56% of its present-day range) and for *G. skottsbergii* (presence reduced by 53% of its present range). But at RCP 8.5, lower occurrence and persistence probabilities were forecasted for *G. skottsbergii* than for *L. flavicans*, with their presence reduced by 53% and 46% of their present-day range, respectively (Fig. 2). The latitudinal, south poleward habitat displacement pattern under both RCP scenarios shows *L. flavicans*' range distribution reduced by a latitude shift of > 1° south (RCP 2.6 and 8.5) and *G. skottsbergii*'s range distribution reduced by a latitude shift of > 1° south at RCP 2.6 and of ~ 2° south at RCP 8.5 from their current occupation (Fig. 3) to the year 2050.

## Discussion

Climate-induced distributional shifts of key, habitat-forming species of commercial importance can have severe socio-economic and socio-ecological impacts at local and regional scales. We present the first quantitative projection of the effects of climate change on the natural range distribution of seaweed species of significant biological and marketable interest in the subpolar tip of South America. In the unique ecoregion of the Cape Horn Biosphere Reserve and Chile-

testing and the evaluation scores: the area under the curve (AUC) and the true skill statistics (TSS) for the models' validation (splitting data in 80% for training and 20% for testing) and the evaluation scores for the final models (using 100% of data)



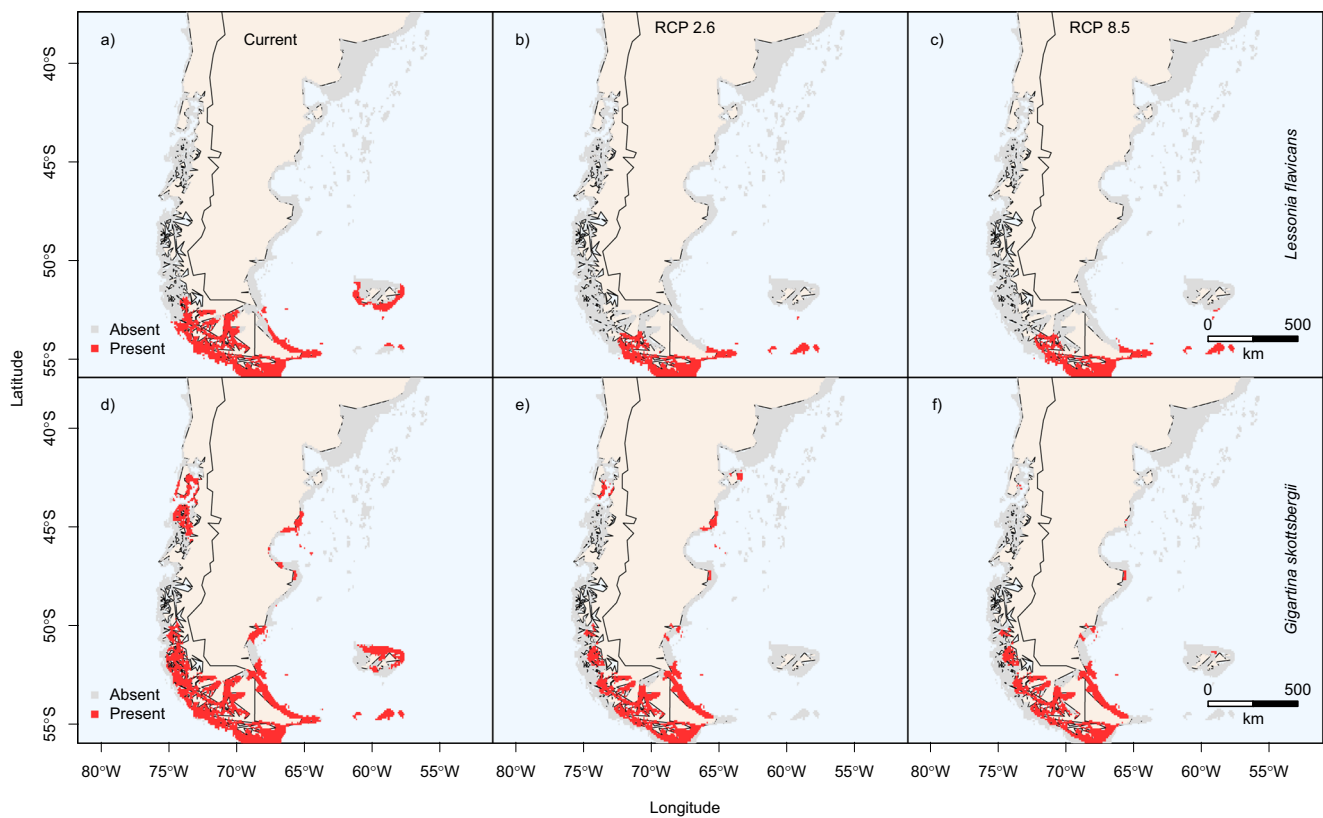
**Fig. 1** Predicted habitat suitability shifts under current (a, d) and future climate trends: at RCP 2.6 (b, e) and RCP 8.5 (c, f) for two seaweed species of significant socio-economic and socio-ecological importance

along the coastlines of the Subantarctic tip of South America: *Lessonia flavicans* (a–c) and *Gigartina skottsbergii* (d–f) by the year 2050

Argentina's Subantarctic archipelago, *L. flavicans* and *G. skottsbergii* play crucial socio-economic, cultural, and biological roles similar to those of many Laminariales and Fucales in temperate regions (Wiencke and Amsler 2012; Ojeda et al. 2018). But global climate change and its environmental consequences (e.g., rising ocean temperature, ice melt, sea level rise) threaten their persistence and the goods and services they provide. Our projection of the SDMs for *L. flavicans* and *G. skottsbergii* to the Subantarctic archipelago's environmental conditions as early as 30–35 years into the (near) future displays a significant south poleward shift in the predicted and realized northern range limits, and consequently reduced niche size for both algae species. The poleward retraction of the species range seems to be driven mainly by temperature, but nutrient availability in these subpolar waters is also key to the seaweeds' physiological performance (Fraser 2016; Franco et al. 2018; Williamson et al. 2019). Maximum sea surface temperature was a direct range-limiting factor for *L. flavicans* and *G. skottsbergii*, as was minimum nitrate concentrations. This may suggest that these two species could be more sensitive and/or have lower physio-evolutionary adaptation means to increasing seawater temperatures, and accordingly reduced nutrient levels, than other marine taxa in subpolar habitats.

Both *L. flavicans* and *G. skottsbergii* in the Subantarctic western Atlantic and Eastern Pacific occur along the shoreline

environments where seawater temperature and nitrate concentrations are tightly correlated (Ayers and Strutton 2013). In general, population persistence and recruitment success of cold-adapted marine algae decrease with rising water temperatures, together with low nutrients (Muth et al. 2019). This makes seaweed populations worldwide vulnerable to imminent global warming (Fraser 2016; Muth et al. 2019), especially the cold-adapted subpolar and polar species. In our models, for instance, the main predictor variables selected were maximum sea surface temperature and minimum nitrate concentrations (e.g., Franco et al. 2018; Muth et al. 2019; Table 1). Together, these variables showed the highest gain contribution explaining *L. flavicans* and *G. skottsbergii* ecological and biogeographic responses to climate changes (next 30–35 years) along the littoral Subantarctic tip of South America. The potential effects of rising temperatures on the stratification of the oceans' upper mixed layer (e.g., upwelling events) have been postulated for many coastal regions given its consequent changes to the dynamics and availability of nutrients, such as iron and nitrogen for foundation species (primary producers; Flukes et al. 2015; Franco et al. 2018; Moore et al. 2018; Oyarzún and Brierley 2019; Williamson et al. 2019). Indeed, in some systems, upwelling regimes (which generally promote cooling) are weakening due to rising sea-surface temperature (e.g., European marine systems),



**Fig. 2** Registered and predicted shifts in presence/absence of two seaweed species of significant socio-economic and socio-ecological importance along the coastlines of the Subantarctic tip of South

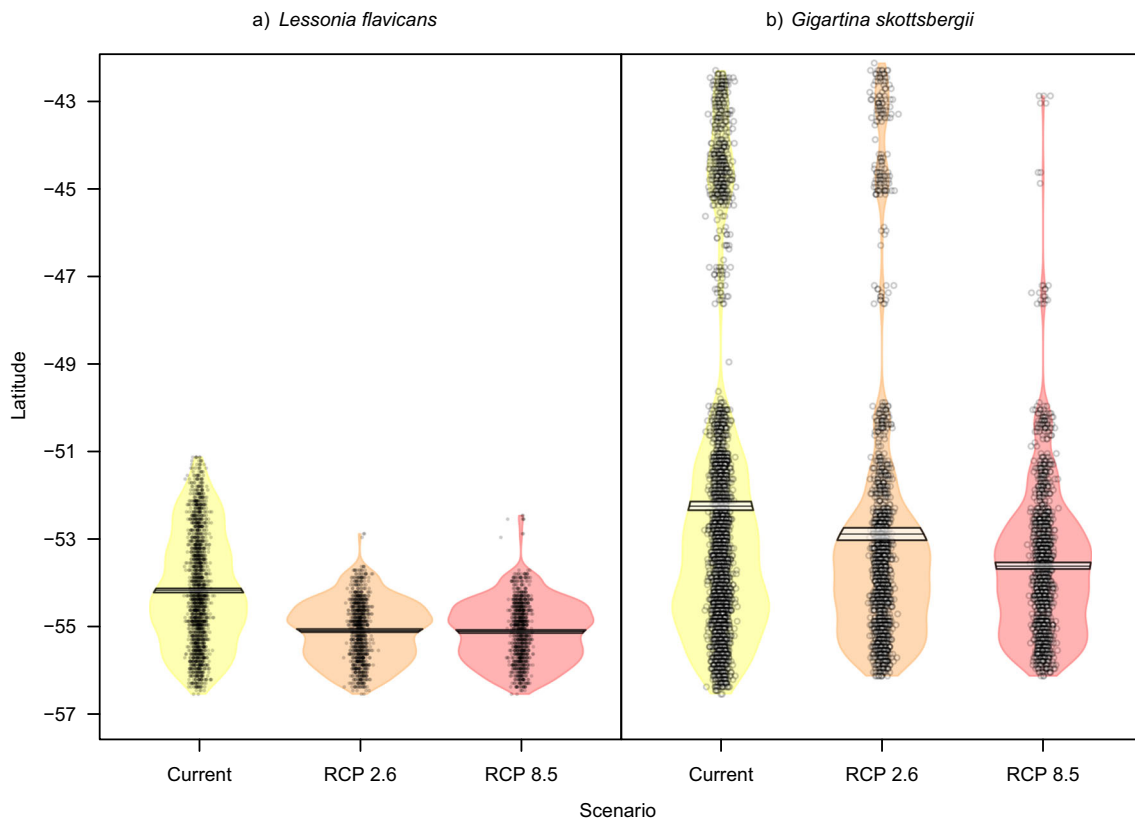
America: *Lessonia flavicans* (a–c) and *Gigartina skottsbergii* (d–f), under current (a, d) and future climate trend scenarios (IPCC 2014): RCP 2.6 (b, e) and RCP 8.5 (c, f) by the year 2050

affecting seaweed eco-physiology (Franco et al. 2018 and references therein). Rising temperatures are also reducing the thickness and duration of snow and ice cover, which leads to increased exposure of seaweeds to solar UV radiation (Williamson et al. 2019). The Subantarctic South American marine system is mainly stratified by salinity near the surface, but unwanted thermal stratification could be introduced to the system under globally altered climate regimes, affecting hydrographic features and biological productivity (e.g., Harley et al. 2006; Franco et al. 2018; Moore et al. 2018; Iriarte 2018). This will change nitrate/nutrient-rich water dynamics and availability for *L. flavicans* and *G. skottsbergii*'s physiology, productivity, and distribution.

The knowledge gained in recent years on the interactive effects of climate change factors (e.g., temperature) and ozone depletion on marine ecosystems ratifies the importance of research considering synergies between environmental factors (Williamson et al. 2019). Such interactive climate change effects might limit the seaweeds' most sensitive life phases: spore recruitment and normal development of embryos (e.g., Nielsen et al. 2014; Muth et al. 2019), as well as growth, reproduction, physiology, and survival (Flukes et al. 2015; Piñeiro et al. 2017; Franco et al. 2018; Muth et al. 2019; Oyarzún and Brierley 2019; Williamson et al. 2019). Substantial declines of habitat-forming seaweeds similar to our study species (e.g., giant kelp

*Macrocystis pyrifera*, *Phyllospora comosa*) in other littoral zones of the Southern Hemisphere were also attributed to above-average seawater temperatures and its associated influx of nutrient-poor waters (e.g., Eastern Australia; Wernberg et al. 2011; Flukes et al. 2015). Not only biomass but also seaweeds' quality is affected when protective compounds produced by algae increase with solar exposure (Harley et al. 2006; Williamson et al. 2019). This lowers the quality of commercial seaweeds (e.g., *L. flavicans*, *G. skottsbergii*) and that of their dependent fish and invertebrates of high marketable value as well (e.g., sea urchins *Pseudechinus magellanicus* or king crab *Lithodes santolla*). We therefore advise that future seaweed SDMs in sub-polar regions integrate data from multi-factor experiments (e.g., recruitment), from multiple environmental conditions (e.g., temperature, solar radiation, upwelling current regimes), and from algal physiology (e.g., photosynthesis). This is central to aid estimates of mechanistic and/or correlative climate-induced shifting in habitat distribution of bio- and socio-economically key species and its plausible aftermath.

Climate-induced environmental changes cascade across different trophic levels. Changes to herbivory, for instance, have been linked to worldwide ocean warming, showing a poleward range shift of tropical herbivores and consequent deforestation of temperate algal forests of vital, habitat-forming species (Steneck et al. 2002; Franco et al. 2015,



**Fig. 3** Projected latitude shifts in degrees South polewards of two seaweed species of significant socio-economic and socio-ecological importance along the coastlines of the Subantarctic tip of South America: *Lessonia*

*flavicans* (a) and *Gigartina skottsbergii* (b) under current and future climate trends, RCP 2.6 and RCP 8.5 (IPCC 2014) by the year 2050. Black lines show the mean latitude shifts and 95% confidence intervals

2018, Vergés et al. 2016). Such top-down seaweed deforestation from herbivory is not common in Subantarctic Chile (Santelices and Ojeda 1984) and Argentina (Dayton 1985; Steneck et al. 2002). But this may be only a matter of time, as climate-driven “tropicalization” of temperate marine communities is occurring globally and it has significant socio-economic and management repercussions (Vergés et al. 2016; Oyarzún and Brierley 2019). Our results suggest that these climate-driven shifting of habitat types can have major consequences for habitat-forming primary producers such as *L. flavicans* and *G. skottsbergii* (rising temperature, CO<sub>2</sub> levels, UV radiation; Bischof et al. 1998; Steneck et al. 2002; Harley et al. 2006; Williamson et al. 2019) reducing their latitudinal and depth ranges (Figs. 2 and 3). Other, less climate-sensitive primary producers and seaweed species could replace *L. flavicans* and *G. skottsbergii* in Chile’s and Argentina’s Subantarctic shorelines, but this can be detrimental to the benthic habitats (e.g., Harley et al. 2006), to their associated organisms of economic importance (e.g., king crab *Lithodes santolla*), and to the coastal communities dependent on them (e.g., Wiencke and Amsler 2012; Sudha 2017; Anis et al. 2017; Iriarte 2018; Ojeda et al. 2018).

Despite the great utility of SDMs to identify influential variables restricting suitable habitat for bio-commercially important

seaweed populations, uncertainties are part of any predictive modeling approach (Cheung et al. 2009, Austin and Van Niel 2011). Reliable absence data for instance, are difficult to gather and may be overestimated for species with cryptic life phases, such as seaweeds’ spore stages (e.g., Ranc et al. 2017). We combined occurrence records and suitable habitat data to model *L. flavicans*’ and *G. skottsbergii*’s future range, using GBIF data to fit and apply the SDMs (Anderson et al. 2016). The information from global datasets, used to calibrate the SDMs, include data collected using different sampling, taxonomic, and observational methods, which can generate sampling bias (Anderson et al. 2016; Ranc et al. 2017). Also, the predictive power of SDMs may be biased when solar radiation measures and/or physiology data—determining range boundaries (Franco et al. 2018)—are excluded from model parameters, or it may lose power when extrapolated to new environments (Evans et al. 2016). It was beyond the scope of this study to include data on *L. flavicans*’ or *G. skottsbergii*’s physiology (e.g., photosynthetic parameters, such as chlorophyll fluorescence or electron transport rate, light) from the 216 study sites to model their future range distributions in the Subantarctic tip of South America. However, we included the environmental parameters bio-physiologically relevant to each species. We are currently gathering photosynthetic and physiological data for both, and additional, endemic

seaweed species in the region using interdisciplinary and complementary approaches (e.g., genomic analyses, PAM-fluorometry, pigment concentrations; i.e., FONDECYT Grant #1180433 to AM). These data will be incorporated into our model parameterization in upcoming works to strengthen their predictive power (Evans et al. 2016), their applicability to marine resource management–conservation (Evans et al. 2016; Sofae et al. 2018) and to account for combined biotic and abiotic effects on range distribution of marine organisms.

Among the most difficult challenges facing ecologists and policy makers today is to understand how marine ecosystems—and the commercial goods and services they offer—will respond to novel environmental conditions caused by climate changes (Harley et al. 2006). It is difficult to precisely predict future temperatures, nutrients, solar radiation levels, CO<sub>2</sub> concentrations, and other marine habitat conditions in the Chile–Argentina Subantarctic archipelago. Future action recommendations could aim at increasing the resilience of marine communities to climate stressors, and at improved monitoring of abiotic changes (e.g., Strain et al. 2015). These may include the use of management tools of climate-driven environmental changes at local and regional scales, and/or the use of remote sensing tools to monitor spatiotemporal variability in environmental conditions (e.g., temperature, ice-cover, CO<sub>2</sub>) across local to global scales (Cheung et al. 2009; Muth et al. 2019; Williamson et al. 2019). Our results provide baseline information on the socio-ecological fragility of commercially important and habitat-forming seaweed species in Subantarctic marine habitats in response to upcoming (30–35 years) environmental changes. These are vital data for conservation and management of key natural resources in a biologically, socio-ecologically, and ethno-culturally unique region of the world.

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