

Regional Suitability Assessment for the Mouseear Hawkweed (*Hieracium pilosella*) Invasion in Patagonian Rangelands

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Several studies have been carried out to evaluate the main drivers behind biological invasions and their ecological consequences. Nevertheless, it is still extremely difficult to acquire a full understanding of the invasion process due to its high level of complexity. The problems that complicate invasion studies are low detection during the early stages of invasion, and the high survey cost of working over large, inaccessible, and rugged areas. The studies that develop efficient tools to reduce costs and time will help to control or mitigate the invaders' damaging effects. *Hieracium pilosella* is an aggressive invader of grasslands worldwide. The aim of this work was to conduct a regional assessment for the suitability of *H. pilosella* invasion in the Fuegian Steppe by combining field surveys, spatial modeling, and geographic information system tools. We recorded the invader cover in 167 sample sites and we determined the relationship between environmental variables and the probability of invasion. This was carried out by the selection of alternative generalized linear models. The best model indicates that disturbance and plant community were the main drivers to predict invasion suitability on a regional scale. Therefore, these two variables were used as main inputs to construct a regional invasion suitability map, which identifies the most critical areas for prevention, control, and further monitoring. This approach corresponds to a tool that permits us to evaluate the suitability of invasion even over large and inaccessible areas. The results especially warn about soil disturbance associated with usual management practices in Fuegian rangelands.

Nomenclature: Mouseear hawkweed, *Hieracium pilosella* L.

Key Words: Grasslands, hawkweeds, NIS, pastures, sheep grazing, soil disturbance, spatial modeling, suitability.

Nonindigenous species (NIS), which threaten global diversity, are the cause of ecological and economic damage in several ecosystems (Shrader-Frechette 2001; Vitousek et al. 1996). Moreover, the extent and ecological impact of NIS has increased rapidly over the past half century because of increasing globalization (Pyšek and Richardson 2010). Knowledge of the main drivers behind the biological invasions and their ecological consequences is clearly

improving. However, it is still difficult to acquire a full understanding of the invasion process due to its high complexity (Pyšek and Richardson 2010). It is for this reason that researchers continue developing tools to predict, control, or mitigate NIS invasions and their damaging effects.

In an early invasion process, sparsely distributed individuals are difficult to detect. Consequently, the invader population remains undetected until it reaches a threshold density (Mack et al. 2000; Maxwell et al. 2012). Hence, in extensively managed lands, conventional sampling methods are generally rather ineffective. Therefore, sampling size must be increased to encompass large areas, and rapid fieldwork becomes inefficient in costs and time. Conventional sampling methods have the additional shortcoming of having a high probability of missing large invader populations due to uninformed random searching (Cacho et al. 2006). Hence, in a new worldwide scenario of high NIS mobilization, the use of predictive tools able to cope quickly and economically with large spatial scales is essential. These tools would optimize efforts and resources, and would increase the probability of the early detection

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Management Implications

Habitat suitability evaluations have been used for several scientific or management issues. They have been particularly useful in the ecology of invasions, to evaluate the effect of different environmental variables regarding invader spread and population dynamics. The approach presented in this work integrates field surveys, spatial modeling, and GIS tools to assess the suitability of invasion in an early stage of the invasion process, and over large areas. Even more, fieldwork effort and cost can be reduced, allowing for a more effective invasion detection, control, and monitoring.

and thereby become an effective invader control or eradication plan (Kaplan et al. 2014).

Spatial modeling is a practical, useful, and promising tool for ecological management (Guisan and Zimmermann 2000; He et al. 2011). It can be used to improve the capacity for monitoring changes over time and large extents, thereby reducing the high cost associated with field sampling over the whole extent of many invasions (Bradley and Mustard 2006; He et al. 2011). Habitat suitability models (also termed species distribution models, ecological niche models, or bioclimatic envelope models) use empirical relationships between a species' distribution and environmental variables to predict potential suitable habitats across a landscape or region (Bradley et al. 2012). Quantification of the relationship between a NIS distribution and environment is one of the most important aspects of predictive modeling in ecology (Guisan and Zimmermann 2000). Likewise, the widespread use of remote sensing and geographic information systems (GIS) permits the collection, integration, compilation, organization, and display of spatial data (Yassemi et al. 2008). These digital tools have become an indispensable part of environmental modeling technology to manage and analyze increasingly complex and diverse environmental data (Hunt et al. 2010; Yassemi et al. 2008). The integration of GIS and spatio-temporal models has been the subject of active research and has been increasing in recent years (Yassemi et al. 2008).

In addition to the identification of vulnerable areas for invasions, habitat suitability predictions have been used for other scientific or management issues. In invasion ecology, they are particularly useful in predicting spread pathways of invasive plant species (Butcher and Kelly 2011; Peltzer et al. 2008; Vanderhoof et al. 2009). In this sense, spatially explicit models have been used to investigate exotic species invasions and the effect of different environmental variables on invader spreading and population dynamics (Higgins and Richardson 1996; Higgins et al. 2001; Rees and Hill 2001). Spatial modeling also facilitates the localization of key sites to prioritize search efforts in invasion monitoring and control (Kaplan et al. 2014). In the last few years, there

has been a strong tendency to develop different techniques to quantify the spreading risk of invasion in different habitats (Pyšek and Richardson 2010; Thomas and Moloney 2015), considering the invasion process acting at different spatial scales (Kaplan et al. 2014).

The aim of this work was to carry out a regional assessment of the invasion suitability in the Fuegian Steppe of an aggressive invader of grasslands worldwide, the yellow mouseear hawkweed (*Hieracium pilosella* L.). To determine the environmental suitability, we calculated the probability of occurrence of the species, according to predictive variables. We combined field surveys, modeling techniques, and GIS tools to generate an environmental suitability map for the mouseear hawkweed invasion. The current assessment facilitates the recognition of the most vulnerable areas on a regional scale, where most efforts should be directed for early detection and control.

Materials and Methods

Invasive Plant Species. *Hieracium pilosella* (syn. *Pilosella officinarum*; Asteraceae) is a dicotyledonous herb native to Eurasia (Bishop and Davy 1994), which aggressively invades different grasslands around the world, such as New Zealand (Treskonova 1991), the United States (Vander Kloet 1978), Switzerland (Winkler and Stöcklin 2002), and Chile (Covacevich 2009). It is becoming abundant in tussock grasslands of the Chilean sector of the Fuegian Steppe (Covacevich 2009). In Argentina, the first report of *H. pilosella* in the steppe of Tierra del Fuego was in 1993 (Livraghi et al. 1998). In previous regional vegetation censuses (between 1985 and 1989), the exotic species was not detected (Collantes et al. 1999). Currently, the species occurs in the entire steppe region with a frequency of 66%, a mean cover less than 2%, and a clear aggregated spatial pattern (Cipriotti et al. 2010).

After colonization, this perennial species gradually forms dense and prostrate mats that exclude other species, reducing forage resources (Treskonova 1991). It is common in dry, poor, and degraded grasslands (Bishop and Davy 1994), and it is very efficient in nutrient pulse capture and use (Fan and Harris 1996). This species tolerates drought and frost, and is present in a wide range of soil types and pH values (Bishop and Davy 1994). It can reproduce by stolons, which are stimulated by grazing (Covacevich 2009), and by sexually or apomictically generated seeds, which are efficiently dispersed by the wind (Sheepens 1994).

In the Argentinean Fuegian grasslands, where domestic sheep have been grazing for 120 yr (Anchorena et al. 2001), high cover of *H. pilosella* was associated with sporadic disturbance events such as shrub clearing, soil ploughing,

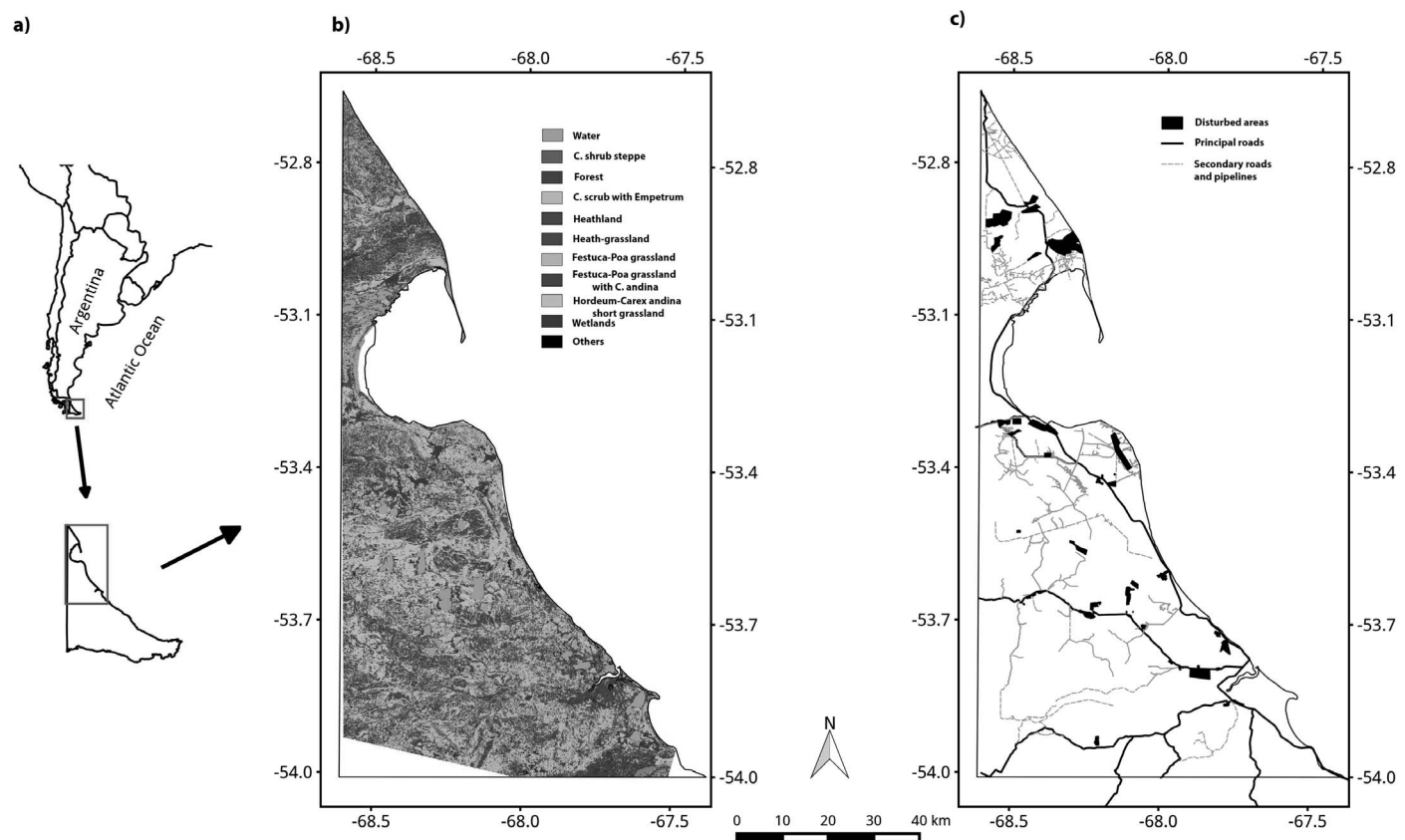


Figure 1. (a) Study area: Tierra del Fuego Island in the southern extreme of South America. (b) Plant communities map used as input for the suitability map. (c) Disturbance map used as input for the suitability map. Lines represent roads and pipelines, whereas polygons represent old pastures or burnt areas. (Color for this figure is available in the online version of this article.)

oil pipelines either under construction or already in place, and pasture establishment, as well as road construction (Cipriotti et al. 2010; Rauber et al. 2014). Most of these events generate, at least temporally, high levels of bare ground cover. Results from other studies indicate that *H. pilosella* success is associated with disturbances like fire and overgrazing (Foran et al. 1992; Jesson et al. 2000; O'Connor et al. 1999; Rose et al. 1998; Treskonova 1991). This is probably due to the fact that this species grows better in sites with an open canopy and short vegetation, with high light availability at ground level and nutrient pulses (Bishop and Davy 1994; Köhler et al. 2005).

Study Area. This work was conducted in the Fuegian Steppe, an approximately 5,000-km² (approximated 1,900-mi²) area in the northern Argentinean sector of the Tierra del Fuego Island (Figure 1a). The area presents a climatic gradient, with mean annual precipitation of over 300 to 450 mm (12 to 18 in), and mean summer temperature under 11 to 8.5 C (52 to 47 F) in a northeast to southwest direction. On a regional scale, upland vegetation is

controlled by climate and lithology (Collantes et al. 1999). Tussock grasslands of coirón (*Festuca gracillima* Hooker f.) dominate the area. Toward the south, soils increase their acidity, because of higher leaching and lower temperature, promoting the acidic variants of the steppe, characterized by dwarf shrubs such as murtilla (*Empetrum rubrum* Vahl ex Willd). On a landscape scale, topographic moisture determines a gradient toward scrubs of *Chilictrichum diffusum* (Foster f.) O. Kunze on the deeper soils, and toward *Poa spiciformis* (Steud.) Hauman & Parodi grasses on dry, north-facing slopes. Extensive eroded heathlands, as well as most grasses, are attributed to heavy sheep grazing and trampling of former tussock grasslands and shrub-steppes (Anchorena et al. 2001; Collantes et al. 1999).

Field Survey. We based our field survey for the mouseear hawkweed invasion on a previous vegetation description of the area. First, we georeferenced a previous vegetation map (Anchorena et al. 2016), which has an accuracy that exceeds 80%, validated by around 200 vegetation–soil

surveys, 600 physiognomic observations from regional inventories, and ad-hoc field trips. Anchorena and collaborators mapped vegetation (Anchorena et al. 2016) based on field surveys and by performing a supervised classification of Landsat Enhanced Thematic Mapper scenes using the maximum likelihood algorithm as a decision rule to assign a pixel into a class. Following supervised classification of the spectral data, extensive postclassification GIS procedures, using ancillary datasets such as digital elevation model, as well as manual editing, were undertaken to reduce confusion between classes. The final map was quantitatively evaluated by computing a confusion matrix and calculating the overall, user's, and producer's accuracies using an independent subset of surveys and observations. Based on this georeferenced map, we selected 167 sample sites in a stratified random way according to main community types from the regional vegetation map and the disturbance occurrence across the steppe region. These sample sites were independent from those of the vegetation map development and evaluation.

In each of the 167 sites, we recorded the *H. pilosella* cover, and we characterized the vegetation community. To record the *H. pilosella* cover, we measured the size of each patch using two orthogonal diameters from the maximum dimension within a plot of 50 by 50 m (164 by 164 ft). To characterize the vegetation community, we recorded the plant species and bare soil cover using the line-intercept method along a 20-m transect randomly placed inside the 50- by 50-m plot. All vegetation and bare soil intercepting the line was recorded. In addition, an expert conducted a full floristic inventory and abundance classification through the modified Braun-Blanquet method (Mueller-Dombois and Ellenberg 1974), performed through a survey in the whole 50- by 50-m. sampling area. Results of this floristic survey were reported in Rauber et al. (2013). Using these data, sites were assigned to a plant community according to detailed descriptions provided in Collantes et al. (1999).

Input for Suitability Map. To construct the suitability map, we first determined the relationship between environmental variables and the invasion probability by means of contrasting alternative generalized linear models (see "Model Estimation" section, below). As predictive variables, we analyzed plant communities, disturbance occurrences, and geographic coordinates, which implicate precipitation and temperature gradients.

To construct the plant community layer used as input for the suitability map (Figure 1b), we used the vegetation map (Anchorena et al. 2016). We considered as a disturbance all those practices that implicate the modification of natural vegetation canopy or the upper soil layer by plowing, by other types of heavy machinery, or by fire.

We excluded the role of wild or domestic grazing from our definition. In this sense, we identified five main disturbance sources in the Fuegian Steppe: old pastures, oil pipelines, oil drilling platforms, roads, and fires. Pasture was a common management practice during the 1970s and 1980s that implied multiple disturbances like the removal of natural vegetation (scrublands), controlled burns, and soil plowing with heavy machines before the sowing of forage species. Oil pipeline establishment also implies soil removal and trenches to bury the pipes. The oil drilling platforms imply soil destruction; but platforms render the soil be unsuitable for vegetation since they are filled with rocky substrate. Road maintenance, as well as roadside improvements, implies soil modification by machinery. Natural or planned fires occur occasionally, modifying the vegetation over extensive areas.

To identify disturbed areas, and to construct the disturbance layer as input for the suitability map (Figure 1c), we used georeferenced maps provided by government agencies such as the Natural Resources Secretariat of the Tierra del Fuego Province. This governmental agency compiles natural resource management information about the region based on ad hoc surveys and information provided by ranchers and oil companies. The disturbance maps show the areas with pastures, oil pipelines, roads, and fires. Oil drilling platforms were not included due to their general vegetation unsuitability. In this context, we considered the disturbance as a categorical variable in accordance with our previous definition.

Model Estimation. To determine the invasion probability in each site, we fit a generalized linear model (McCullagh and Nelder 1989) to relate mouseear hawkweed invasion stages with environmental drivers. We defined three different stages of invasion according to different invader cover (0%, 0 to 1%, > 1%). We assumed that a species cover higher than 1% represents an indicative value for easy detection in field surveys, and at the same time is representative of an early but persistent invasion stage that probably deserves management or control action. On the other hand, a single rosette of three to five leaves and 3 to 5 cm (approximately 1 to 2 in) in diameter can easily escape the visual inspection of field surveys of 50- by 50-m plots. In addition, from demographic studies in New Zealand (Espie 2005), hawkweed cover remains during long periods (15 to 20 yr) below or near 1% cover, and suddenly increases to reach values ca. 30 to 50% in less than 10 yr. Hence, we consider a cover of 1% as a practical threshold to model *H. pilosella* invasion on a regional scale. Then, we fitted a model with multinomial ordinal distribution and logit linking function (Faraway 2006; McCullagh and Nelder 1989; Zuur et al. 2009) to predict the probability of

Table 1. Ranking for the top 10 generalized models (A to J) to predict the *Hieracium pilosella* invasion. Predictors, number of parameters, Akaike information criteria, likelihood ratio tests, and associated P values are indicated. Models follow an ordinal multinomial distribution with a logit linking function for different invasion stages (0 to 2) as response variables and different categorical (plant community and disturbance) and continuous (latitude and longitude) predictors.

Model	Predictors†	Np	AIC	Likelihood ratio test—chi-square	P value
A	PC + D + PC×D	12	548.75	73.996	< 0.00001
B	PC + D + Lon + PC×D	13	549.93	74.816	< 0.00001
C	PC + D	7	550.15	62.593	< 0.00001
D	PC + Lat + PC×Lat	13	550.74	74.008	< 0.00001
E	PC + D + Lon	8	551.51	63.241	< 0.00001
F	PC + D + Lon + Lat + PC×D	14	551.60	75.143	< 0.00001
G	PC + D + Lat	8	552.15	62.594	< 0.00001
H	PC + D + Lon + Lat + Lon×Lat	9	553.03	63.713	< 0.00001
I	D + Lon + D×Lon	8	554.76	59.989	< 0.00001
J	D + Lat + D×Lat	8	555.92	58.823	< 0.00001

Abbreviations: Np, number of parameters; AIC, Akaike information criterion; PC, plant community; D, disturbance; Lat, latitude; Lon, longitude.

H. pilosella cover higher than 1%, given a set of n predictor variables, where p is *H. pilosella* invasion probability for covers higher than 1%.

$$p = \frac{e^{(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n)}}{1 + e^{(\beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_n X_n)}} [1] (\text{Zuuretal.2009})$$

where β_0 is the intercept value, β_1 is the parameter for the X_1 predictor, β_2 is the parameter for the X_2 predictor, and so on, where the β_n is the parameter for the X_n predictor.

We evaluated alternative models, and chose the most parsimonious and predictive, according to the Akaike information criterion (Boyce et al. 2002; Burnham and Anderson 2002). Then, we determined the probability of an invader cover higher than 1% for the combination of all levels from the significant predictive variables derived from the best model.

Construction of the Suitability Map. To obtain the suitability map we overlapped two main rasters, one for each predictive variable derived from the best model to explain current invasion patterns (QGIS software, version 2.12, Quantum GIS Development Team, Quantum GIS Geographic Information System, Open Source Geospatial Foundation Project). According to the results of the previous section, the first raster represents the plant communities and the second one, the disturbed areas. On each site, we assigned the probability of *H. pilosella* invasions according to fit coefficients from the generalized linear model.

Field results indicate that invasion probability of *H. pilosella* decreases about 2.2×10^{-4} by meter (F. De Larminat, unpublished data) from highly invaded areas.

For this evaluation, De Larminat and collaborators recorded *H. pilosella* occurrence in a systematic survey of 203 points on transects of 5 to 12 km long, in 12 directions from a very big patch (ca. 1 ha [2.5 ac]) located in a small paddock near a road. They used these records to model the decrease in the probability of occurrence of the invader, related to distance from the invasion hot spot. This survey was made in 2012 and 2013 and it is completely independent from the regional dataset here presented. We used this information to establish influence areas, where the probability of invasion decreases for each community from highly disturbed areas, such as pastures and main roads, until a maximum distance of 2,000 m, where invasion probability falls below half that of the hot spot.

Results and Discussion

Among the environmental predictors here analyzed, disturbance and plant community were the most important drivers to explain the *H. pilosella* invasion. They conform the best model to predict invasion suitability of *H. pilosella* on a regional scale, according to the Akaike information criterion (Table 1). Disturbance raises the invasion probability from 4.5 to 9.6 times with respect to the nondisturbed areas according to each community (Table 2). The invasion probability of each combination of predictive variables was used to construct the suitability map (Figure 2). The suitability map identifies those areas with high environmental suitability for invader cover higher than 1%, as well as zones of low probability for invasion or complete absence of invaders. The residual deviance of the selected model was 222.9 and the respective percentage of correct classification was 85.6% for the

Table 2. Estimated regression parameters (β) and standard error for each predictive variable and levels. Heathlands and absence of disturbance were the baseline of the fitted parameters for the other levels. Communities correspond to TWINSPAN groups.

Variable	β	SE	Wald statistic	P value
Intercept	-2.01	0.34	33.88	< 0.0001
Heath-grassland	-1.27	0.36	12.18	0.0005
<i>Chiliodactylon</i> scrub with <i>Empetrum</i>	0.18	0.37	0.25	0.616
<i>Festuca-Poa</i> grassland	0.47	0.41	1.34	0.247
<i>Chiliodactylon</i> shrub steppe	1.30	0.47	7.63	0.006
<i>Festuca-Poa</i> grassland with <i>Carex andina</i>	-0.35	0.416	0.71	0.398
<i>Hordeum-Carex andina</i> short grassland	0.65	0.59	1.21	0.271
Disturbance occurrence	1.18	0.32	13.72	0.0002

mapped class (invader cover higher than 1%), and 68.9% for all classes.

On the map, invasion probability appears highest over very distinctive corridors and some areas that occur within the study area. These corridors indicate mostly roads and pipelines, while other areas represent pasture paddocks or fires. Differences in the suitability of disturbed sites result from the presence of different plant communities and, according to the generalized model, the probability of occurrence in different disturbed plant communities differs. Among the plant communities, the disturbed shrub steppes are the most suitable sites for the spreading of this invasive species. The suitability map facilitates the identification of highly suitable sites for *H. pilosella* invasion, as well as the occurrence of unsuitable sites to the invader colonization and spread. There are large extents with very low invasion probability, where the species is not successful. These large extensions correspond to undisturbed plant communities with very low suitability conditions for *H. pilosella* in areas with more acidic environments, like heathlands or humid communities like wetlands or salt marshlands. This assessment warns especially about soil disturbance associated with management practices in rangelands, like pastures, shrub removal, burns or wildfires, and roadside improvement, among others.

Anthropogenic disturbances are one of the most important factors determining the spread of several NIS around the world (Estrada and Flory 2015; Hernández et al. 2014; Lonsdale 1999; Mandal and Joshi 2014), highlighting the human role in the invasion success. Previous reports have already advised about the importance of disturbance and plant community in *H. pilosella* extent in the Fuegian Steppe (Cipriotti et al. 2010; Rauber et al. 2014), but have not considered the major environmental drivers on an integrated regional map. The high spread ability of this species and its efficient nutrient pulse exploitation (Bishop and Davy 1994; Köhler et al. 2005) would make disturbed areas of the steppe highly vulnerable

to invasion due to the bare ground patches generated by the disturbances.

The association between *H. pilosella* invasion probability and plant communities corresponds to a gradient in soil fertility from upland communities. Among plant communities, shrub steppes codominated by *Chiliodactylon diffusum* shrubs and fescue tussocks (*Festuca gracillima*) had the higher invasion probability. They had 11.91 and 6.64 % higher invasion probability values than the acidic heathlands and heath-grasslands (Table 3). *Festuca-Poa* grasslands and *Chiliodactylon* scrub are the types of habitat with better conditions for biological production (Collantes et al. 1999). Their soils have good nutrient status, relatively fine texture, adequate organic matter content, and moisture. *Hordeum pubiflorum* (Hooker f.)-*Carex andina* Phil. short grasslands, *Festuca-Poa* grasslands, and *Chiliodactylon* scrubs with *Empetrum* presented the third, fourth, and fifth highest invasion probabilities. They have 6.2, 4.3, and 2.5 % higher invasion probability values than the acidic communities, respectively. *Hordeum-Carex andina* short grasslands, *Festuca-Poa* grasslands, and *Chiliodactylon* scrubs with *Empetrum* have intermediate soil fertility status. Heathlands and heath-grassland had the lowest invasion probability and they are the most acidic and infertile soil communities in the region. Their soils are acidic and infertile (Collantes et al. 1999).

In a previous work, a quadratic relationship between *H. pilosella* and shrub cover was determined (Cipriotti et al. 2010). Invader cover would be higher in those sites with shrub cover of 20 to 30%, which has been attributed to the balance between soil moisture and solar incidence at ground level under this condition. In very dense and closed scrubs, light incidence on the soil surface would be very low, and in extremely open scrubs water loss through evaporation would be very high. In addition, scrubs would be capable of retaining seeds dispersed by the wind more efficiently than other vegetation structures and that would determine higher propagule availability in shrub steppes than in the other plant communities.

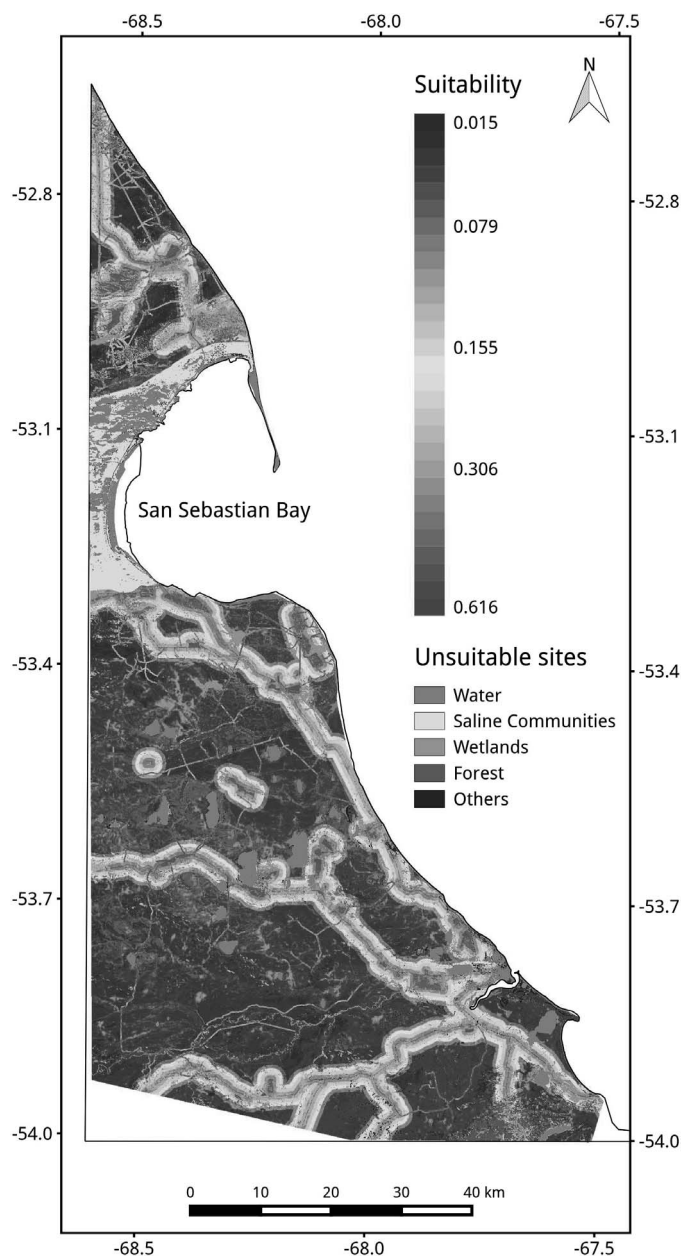


Figure 2. Regional suitability map for the *Hieracium pilosella* invasion in Fuegian Steppe. The quantities mapped represent the probability of *H. pilosella* invasion with cover higher than 1%, according to the fitted generalized linear model. (Color for this figure is available in the online version of this article.)

The zone surrounding the San Sebastian Bay is strongly influenced by the saline water of the sea and was excluded from the map because the invasive species was not found there. It presents large extensions of soil permanently or seasonally flooded, and saline water with higher pH values than the other zones. The vegetation of this bay is characterized by species that tolerate high salinity, belonging to the genera *Puccinellia*, *Lepidophyllum*, and

Sarcocornia. In saline and humid communities, *H. pilosella* was not seen, probably because they are not propitious environments for colonization of this species. In the very hostile environment of the acidic communities, *H. pilosella* was present, but in a very low cover, indicating propagule availability but environmental restrictions for population growth. Saline and acidic communities occupy broad and extensive lands, and, because of their shape, impede more efficiently the *H. pilosella* spread and colonization than wetlands, which occupy valleys, generally forming narrow corridors.

Habitat suitability models have been used for risk analyses for several invasive species (Andrew and Ustin 2009; David and Menges 2011; Hirzel and Le Lay 2008; Rameshprabu and Swamy 2013; Rodder and Lotters 2010). Close matches between environmental components of the ecological habitat suitability and patterns of occurrence of species on a regional scale encourage the use of this tool for regional distributional predictions (Thuiller et al. 2005). Such models depend on survey strategies and the stage of invasion, with more advanced invasion processes providing better model predictions (Vaclavik and Meentemeyer 2012).

The probability of successful invasion depends on the interaction among environmental suitability of local microsites, arriving propagules, and climate (Chytrý et al. 2008; Lockwood et al. 2005; Warren et al. 2012). In our logistic model, the interaction between environmental suitability and propagule pressure was mixed, because it was estimated on invader cover in each environment. In the study area, the species had a high constancy, but a generally low cover, with some hot spots of very high abundance (Cipriotti et al. 2010). We do not have a validation for our model, because there are not enough observations, principally in independent disturbed sites. Currently, this species is present throughout the Fuegian Steppe, and an updated field survey could help to adjust the model to improve map accuracy and to evaluate the spatial invasion dynamics.

In our study region, sites with an old history of disturbed soils present currently high invader covers (10 to 30%) and as a consequence are the most critical areas for control and further monitoring. Sites with higher invasion suitability correspond to areas with pastures implanted several years ago (Serra 1990), pipelines, and areas with soil removal. Throughout the region, soil must be actively protected from disturbance or be monitored thereafter. New disturbed areas in the region will change the suitability map, making it potentially very dynamic, and independent of the current community distribution.

Species distribution models have been thoroughly recognized as a useful tool that relate the abundance of species to environmental data, identify and describe the processes underlying species distributional patterns, and

Table 3. Punctual and interval ($\alpha = 5\%$) estimates for the probability of *Hieracium pilosella* invasion with cover higher than 1% according to the fitted generalized linear model. The number of surveyed plots (n) for each combination of predictive variables is also indicated.

Community	Disturbance	n	Invasion Probability	Lower limit (95%)	Upper limit (95%)
Heathland	No	10	0.02	0.01	0.05
Heathland	Yes	1	0.14	0.04	0.37
Heath–grassland	No	32	0.01	0.01	0.04
Heath–grassland	Yes	1	0.10	0.04	0.25
<i>Chiliodactylon</i> scrub with <i>Empetrum</i>	No	31	0.05	0.02	0.12
<i>Chiliodactylon</i> scrub with <i>Empetrum</i>	Yes	3	0.35	0.13	0.65
<i>Festuca–Poa</i> grassland	No	23	0.06	0.02	0.21
<i>Festuca–Poa</i> grassland	Yes	4	0.41	0.16	0.73
<i>Chiliodactylon</i> shrub steppe	No	22	0.13	0.05	0.31
<i>Chiliodactylon</i> shrub steppe	Yes	2	0.62	0.28	0.88
<i>Festuca–Poa</i> grassland with <i>C. andina</i>	No	22	0.03	0.01	0.08
<i>Festuca–Poa</i> grassland with <i>C. andina</i>	Yes	1	0.24	0.08	0.52
<i>Hordeum–Carex andina</i> short grassland	No	8	0.07	0.01	0.31
<i>Hordeum–Carex andina</i> short grassland	Yes	4	0.46	0.16	0.79

make predictions concerning species distribution in space and time (Elith and Leathwick 2009; Uden et al. 2015). The a priori determination of environmental suitability permits an early detection of the invasion event, thereby helping prevent invasions or minimize their spread and detrimental effects in vulnerable locations (Peterson 2003; Stephenson et al. 2006; Uden et al. 2015).

This approach corresponds to a tool to evaluate the suitability of invasion over large and inaccessible areas. By employing this tool, fieldwork effort and cost can be reduced, and predictions can be modified principally according to human interventions. The regional and spatially explicit assessment of the environmental drivers and management history on the success of *H. pilosella* provides useful information to identify potential sites for colonization and the spreading of this weed invader in the Fuegian Steppe. As a whole, the information on current distribution and habitat for this exotic species represents an initial step in the development of more complex spatial invasion models, which allow understanding the spread dynamics on a regional scale (Guisan and Zimmermann 2000).

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