Predicting the impacts of climate change on the distribution and conservation of endemic forest land snails of Madeira Island

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ABSTRACT

Climate change is emerging as one of the major threats to natural communities of the world's ecosystems; and biodiversity hotspots, such as Madeira Island, might face a challenging future in the conservation of endangered land snails' species. With this thesis, progresses have been made in order to properly understand the impact of climate on these vulnerable *taxa*; and species distribution models coupled with GIS and climate change scenarios have become crucial to understand the relations between species distribution and environmental conditions, identifying threats and determining biodiversity vulnerability.

With the use of MaxEnt, important changes in the species suitable areas were obtained. Laurel forest species, highly dependent on precipitation and relative humidity, may face major losses on their future suitable areas, leading to the possible extinction of several endangered species, such as *Leiostyla heterodon*.

Despite the complexity of the biological systems, the intrinsic uncertainty of species distribution models and the lack of information about land snails' functional traits, this analysis contributed to a pioneer study on the impacts of climate change on endemic species of Madeira Island. The future inclusion of predictions of the effect of climate change on species distribution as part of IUCN assessments could contribute to species prioritizing, promoting specific management actions and maximizing conservation investment.

Avaliação dos impactos das alterações climáticas na distribuição e conservação dos moluscos terrestres endémicos da floresta da Ilha da Madeira

RESUMO

As alterações climáticas têm sido referenciadas como uma das maiores ameaças às comunidades naturais dos ecossistemas mundiais; sendo que *hotspots* de biodiversidade, como é o exemplo a ilha da Madeira, poderão enfrentar importantes desafios futuros na conservação de espécies ameaçadas de moluscos terrestres. Esta tese pretendeu fornecer algumas pistas para o conhecimento do impacto das alterações climáticas nestes *taxa* vulneráveis. Nesse sentido, os modelos preditivos da distribuição de espécies, acoplados com os SIG e cenários climáticos futuros tornam-se cruciais para compreensão das relações entre a distribuição das espécies e as variáveis ambientais, auxiliando a identificação de ameaças à biodiversidade.

O uso do MaxEnt permitiu identificar importantes alterações nas futuras áreas para distribuição das diferentes espécies. Os moluscos terrestres endémicos da floresta Laurissilva, altamente dependentes da precipitação e humidade relativa, enfrentarão perdas significativas nas áreas potenciais à sua distribuição, as quais poderão, inclusivamente, conduzir à extinção de espécies ameaçadas, como é o caso da *Leiostyla heterodon*.

Não obstante a complexidade dos sistemas biológicos, a incerteza associada aos modelos preditivos, assim como a lacuna no conhecimento relativo aos requisitos funcionais dos moluscos terrestres, esta análise constituiu um estudo pioneiro focado nos impactos das alterações climáticas em espécies de caracóis endémicos da ilha da Madeira. A futura inclusão de modelos preditivos e avaliação do efeito do clima na distribuição das espécies como parte integrante nas avaliações da IUN, poderão contribuir para a priorização na conservação das espécies, promovendo ações de gestão específicas e maximizando o investimento na conservação.

KEYWORDS

Climate change
Predictive models
Land snails
MaxEnt
Geographic Information Systems
Madeira Island

PALAVRAS-CHAVE

Alterações climáticas
Modelos preditivos
Moluscos terrestres
MaxEnt
Sistemas de Informação Geográfica
Ilha da Madeira

ACRONYMS

ASCII: American Standard Code for Information Interchange

AUC: Area under the receiver-operator curve

BIOBASE: Madeira’s Biodiversity Database

CIELO: Clima Insular à Escala Local (Insular Climate at Local Scale)

CLIMAAT: Clima e Meteorologia dos Arquipélagos Atlânticos

COSRAM: Carta de Ocupação de Solos da Região Autónoma da Madeira (Land Cover Map of the Autonomous Region of Madeira)

CR: Critically Endangered

CSV: Comma-separated values

DD: Data deficient

DPAEME: Departamento de Producción de la Agencia Estatal de Meteorología de España

EN: Endangered

ESRI: Environmental Systems Research Institute

EUSHD: European Union Species and Habitats Directive

EX: Extinct

GCM: Global Circulation Models

GIS: Geographic Information System

HadCM3: Hadley Center Coupled Model

IMP: Instituto de Meteorologia de Portugal (currently IPMA: Instituto Português do Mar e da Atmosfera)

IPCC: Intergovernmental Panel on Climate Change

IUCN: International Union for Conservation of Nature

LC: Least Concern

MaxEnt: Maximum Entropy Modeling

Max SSS: Maximizing the sum of sensitivity and specificity

NT: Near Threatened

ROC: Receiver operating characteristic

SAC: Special Areas of Conservation

SDM: Species distribution models

SPA: Special Protection Areas

SRARN: Secretaria Regional do Ambiente e dos Recursos Naturais

TSS: True Skill statistic

UTM: Universal Transverse Mercator

VU: Vulnerable

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1. INTRODUCTION

1.1. Global warming

Global climate is constantly changing, and such changes have impacts on the fauna and flora at all scales. Some particular events, for example the glacial periods of the Pleistocene, have had drastic effects on biodiversity in some parts of the world. In recent times, however, human activities have played an increasingly important role in determining the direction and speed of climate and biodiversity change. The documented increase in anthropogenic greenhouse gas emissions has been causing widespread changes in temperatures since the mid-20th century and its continued increase will accelerate global warming and induce many changes in the global climate system. Current models suggest that even if greenhouse gas concentrations remain stable in the future, warming will continue for several decades, due to the time scales related to climate processes, feedbacks and slow response of the oceans (IPCC, 2007a).

In recent decades, improvements in computational capacity and measuring technology have enabled the creation of sophisticated models of climate change allowing for varying scenarios and assumptions. According to the Intergovernmental Panel on Climate Change (IPCC, 2007a), the best estimate projection for the low emissions scenario applied to the climate system (B1) suggests a global average temperature increase of 1.8 ºC (range from 1.1 ºC to 2.9 ºC), while the best estimation for the high emissions scenario (A1FI) points to 4.0 °C (range from 2.4 °C to 6.4 °C), by 2100.

These models also confirm that other climatic changes already observed will accelerate. These include the unprecedented extensive melting surface of glaciers, changes in wind patterns and precipitation, in sea levels and salinity, and in the increased frequency and intensity of extreme climatic events, including droughts, heat waves, intense rainfall, and cyclones.

These changes have major ecological, social and economic implications. Some changes will be irreversible, and the mitigation of, and adaptation to such changes has become a priority for many governments' policies. One of the five targets for the strategy defined by the European Union for 2020 is directly related to climate change: the reduction of greenhouse gas emissions to 20% lower than in 1990.

1.2. Biodiversity shifts and loss in a changing world

Climate change is emerging as one of the major threats to natural communities of the world's ecosystems. Mid-range climate change scenarios projected for the next decades (IPCC, 2007a) will create new challenges for biodiversity conservation (IPCC, 2007b; Heller and Zavaleta, 2009), and might increase recent human-caused extinction rates (McLaughlin *et al.*, 2002; Thomas *et al.*, 2004; Malcolm *et al.*, 2006; Pounds *et al.*, 2006). Already, changes in climate have provoked responses at all levels from individuals and species through to changes in community structure and composition. There have been numerous shifts in the distribution and abundance of species (Benning *et al.*, 2002; Peterson *et al.*, 2002; Parmesan and Yohe, 2003; Root *et al.*, 2003; Thomas *et al.*, 2004; Loarie *et al.*, 2008), with consequent community fragmentation and species-level extinction (Parmesan, 2006; Ponce-Reyes *et al.*, 2012; Sax *et al.*, 2013). Phenological changes observed in several populations, such as earlier breeding and migration shifts, are disrupting species interactions (Walther *et al.*, 2002; Cotton, 2003; Crick, 2004; Both and Marvelde, 2007), promoting ecosystem instability.

The IPCC report (2007a, 2007b) makes it clear that the changes in climate are very distinctive across the world. In tropical areas, many species may be forced to move to higher elevations, reducing their distribution range and population size (Peh, 2007; Seimon *et al.*, 2007; Chen *et al.*, 2009, 2011; Velásquez-Tibatá *et al.*, 2013), and the magnitude of the predicted changes suggest that this will induce the loss of numerous species in fragile habitats (Araújo *et al.*, 2004).

1.3. Adapting protected areas

Natural reserves located in higher latitudes and altitudes, coastal and oceanic islands, and protected areas surrounded by unsuitable anthropogenic habitats are at high risk just because there is no scope for the habitats and the species they contain to move in response to changes in the climate system (Shafer, 1999; Sala *et al.*, 2000).

Biodiversity hotspots, with high densities of endemic species which have small range sizes may be particularly vulnerable to climate change (Raxworthy *et al.*, 2008). With the species' shift due to their adaptation to new environmental variables, existing natural reserves and protected areas will no longer accommodate all designated species (Araújo *et al.*, 2004, 2011; Lemieux and Scott, 2005; Thuiller *et al.*, 2006; Heller and Zavaleta, 2009), especially where surrounding areas are unavailable due to human exploitation. Successful mitigation of the impact of climate change on biodiversity will depend on our protection strategies (Hannah *et al.*, 2002). These require a widening of the temporal and spatial perspective in which such strategies are conceived. Climate change scenarios must be factored into such plans (Peters and Darling, 1985; Ferrier and Guisan, 2006; Rounsevell *et al.*, 2006), and require, in addition, the better understanding of species responses to climate change (physiological, behavioural and demographic) (Peters and Darling, 1985; Thomas *et al.*, 2004; Sekercioglu *et al.*, 2007). The creation of buffer zones to increase connectivity among protected areas and to provide space for adaptive shift (Shafer, 1999; Hughes *et al.*, 2003; Chambers *et al.*, 2005; Millar *et al.*, 2007) is one of the main recommendations for climate change adaptation strategies for biodiversity. This in turn requires increased coordination among all stakeholders in the region (Araújo *et al.*, 2004; Heller and Zavaleta, 2009).

1.4. Species distribution models as a conservation tool

The effective conservation of biodiversity depends on a very specific set of skills related to analysis of the distribution of species (Araújo and Williams, 2000), and the identification and understanding of the underlying causes of their trends (Teixeira, 2009). In this context, predictive models of species distribution coupled with the use of GIS and climate change scenarios have become crucial to identify threats, and to inform actions to limit loss (Dangermond and Artz, 2010). They have been developed and debated by many workers (e.g. Peters and Darling , 1985; Mulholland *et al.*, 1997; Huang *et al.* 1998; Chornesky *et al.*, 2005; Da Fonseca *et al.*, 2005; Guisan and Thuiller, 2005; Brown, 2006; Ferrier and Guisan, 2006; Rounsevell *et al.*, 2006; Elith and Leathwick, 2009; Heller and Zavaleta, 2009).

Several approaches have been used to assess the impact of climate change on species diversity and community composition (Guisan and Zimmermann 2000; Araújo *et al.*, 2006). Species distribution models (SDMs) are based on the statistical relationship between records of species current distribution and their associated environmental variables. The mutual analysis allows the estimation of the probability of species' occurrence in a particular location and permits the delimitation of potential distribution areas in unsampled locations (Segurado and Araújo, 2004; Hijmans and Graham, 2006; Franklin, 2009). Assuming that species responses to particular environmental variables remain unchanged, these statistical tools can also be used to relate present day distributions with current environmental conditions, and then use future potential climate conditions to predict future species distributions (Pearson and Dawson, 2003).

Because large presence/absence data sets are frequently unavailable and unreliable (Corsi *et al.*, 2000; Elith, 2000; Guisan and Zimmerman, 2000; Scott *et al.*, 2002), a number of recent analyses have used presence-only data (e.g. museum collections; Elith *et al.*, 2011), producing large extent and fine-resolution maps that summarize many of the interactions between species and environment (Bellamy *et al.*, 2013). One of the most popular techniques and best predictive tools (Elith *et al.*, 2006) for modelling species, based on presence-only data, is the algorithm of maximum entropy, available at MaxEnt software (Phillips *et al.*, 2006; Phillips and Dudik, 2008). Launched in 2004, this software has been widely used by a broad panel of researchers, enabling the establishment of correlations between the occurrence of species, mapping and predicting their future distributions under hypothetical climate scenarios (Phillips *et al.*, 2006; Kharouba *et al.*, 2009; Williams *et al.*, 2009; Yates *et al.*, 2010).

There are some difficulties associated with this approach (Webster *et al.*, 2002), and several authors claim that these models generally ignore inter-specific interactions (Davis *et al.*, 1998; Pearson and Dawson, 2003; Araújo and Luoto, 2007); do not consider long-term population viability (Keith *et al.*, 2008); use global circulation models to predict future climate conditions (Thuiller, 2004; Pearson *et al.*, 2006; Beaumont *et al.*, 2008) and often demonstrate residual spatial autocorrelation in data, sampling bias and inadequate testing with independent data (Phillips *et al.* 2009; Veloz, 2009; Merckx *et al.*, 2011).

Nevertheless, these models are able to make reasonable predictions about the consequences of climate change (Araújo *et al.*, 2005a; Huntley *et al.*, 2008), and they can be used with very simple location data. They can be applied to large numbers of species in the same region. They can therefore be applied to assess potential changes in regions where data are not extensive but environments are diverse. They form the basis of the analytical procedures used in this study.

1.5. Oceanic islands under pressure

Oceanic islands and their biota are particularly at risk. Their isolation has resulted in a high level of endemicity; evolution has taken place independently on each archipelago, and they have become model systems for studying ecological and evolutionary processes (Whittaker and Fernández-Palacios, 2007). By definition, the ranges of such endemic species are small, and even local catastrophes can cause extinction. The scope for movement in response to environmental change is extremely limited (Whittaker *et al.*, 2001; Gillespie *et al.*, 2008). Many extinctions have already occurred on such islands as a result of land use changes and the introduction of predators and competitors (Reid and Miller, 1989; Sadler, 1999; Sala *et al.*, 2000; Duncan and Blackburn, 2007; Butchart *et al.*, 2010; Cardoso *et al.*, 2010).

1.6. Madeira geology and climate

Madeira is typical of an oceanic island with unique biodiversity under increasing pressure. Together with other Macaronesian archipelagos (Canaries, Selvagens, Azores), it is placed in the Mediterranean Basin biogeographical region, itself defined as a biodiversity hotspot with many endemic species (Médail and Quézel, 1999; Myers *et al.*, 2000; Mittermeier *et al.*, 2005). Even within this rich area, the Macaronesian archipelagos are notable for the high levels of endemism associated with their oceanic origin.

The Madeiran archipelago lies in the Atlantic Ocean about 1000 km from mainland Portugal, and about 500 km from the African coast. There are three major groups of islands, Madeira itself, Porto Santo, and the Desertas, with a combined land area of c. 740 km^2. It formed over an ocean floor “hotspot”, with several episodes of violent volcanic activity starting 10-15 million years ago (Geldmacher *et al.*, 2000; Prada and Serralheiro, 2000). With a geological age of about 5.2 million years (Geldmacher *et al.*, 2000), Madeira island is 40 km from the older island of Porto Santo (and its offshore islets), separated by deep ocean. The Desertas Islands are closer to Madeira, and are linked to it by a shallow submarine ridge.

The same hotspot that originated the archipelago was also responsible for the creation of what are now seamounts between Portugal and Madeira (Fernández-Palacios *et al.*, 2011). These were once islands or archipelagos, and provided the opportunity for a stepping stone pattern of colonisation over shorter distances than those now separating Madeira from the mainland.

The topography of Madeira Island is characterized by mountains and deep valleys in the interior and rocky cliffs near the coast. The highest points of the island are Pico Ruivo (1862 m above sea level) and Pico do Areeiro (1818 m) which rise about 5300 m above the Madeira abyssal plain (Prada and Serralheiro, 2000). Besides volcanic activity, this archipelago suffered several climatic and sea level changes in the Pliocene and Pleistocene, shifting the distribution and connectivity of vegetation zones (Cameron and Cook, 2001).

According to the Climate Atlas of the Archipelagos of the Canary Islands, Madeira and the Azores (IMP and DPAEME, 2011), Madeira's archipelago has a mild oceanic climate both in winter and summer. Lying in the subtropical region, the climate is influenced by winds from NE and the Canary Islands current, resulting in two major climate types, Temperate and Mediterranean (Capelo *et al.,* 2004, 2007). The complex topography and high altitude of the peaks create many differing microclimatic regimes. Cliffs and ravines provide extremes of exposure to sunlight. The average annual temperature ranges from 8 ºC in the highest peaks, and 18-19 ºC in lower altitudes. Precipitation occurs throughout the year and the average annual accumulated precipitation is greatest at higher altitudes (up to 3400 mm) and minimal in Funchal and on the low eastern peninsula of Ponta de São Lourenço (less than 600 mm) (Santos and Aguiar, 2006). Precipitation is more seasonal on the south coast, with drier summers reflecting the prevalence of northerly winds and the orographic effect of the high mountains in the interior (Santos and Aguiar, 2006). It is here that the climate approaches that of the Mediterranean.

Regional models of climate change, customized to Madeira Island (Azevedo, 1996), indicate a decrease in precipitation of between 5% and 30% throughout the island by the period 2040-2069, and reduction between 20% and 40% by the end of the century. Regions at higher altitude will be most affected by rainfall reduction (Cruz *et al.*, 2009; Figueira *et al.*, 2013). As expected at a global scale (IPCC, 2007a), local climate scenarios also suggest that the average annual temperature will increase by the end of the century. While the low emission scenario (B2) predicts a 1.4 ºC to 2.2 ºC rise, the high emission scenario (A2) forecasts a 2.2 ºC to 3.2 ºC increase in temperature (Santos and Aguiar, 2006).

1.7. Madeiran biodiversity

The Macaronesian biogeographical region, including Madeira, contains about 5000 species and subspecies of endemic terrestrial organisms, with Madeira and Selvagens archipelagos contributing 1419 *taxa* (1128 *taxa* from Madeira island) (Izquierdo *et al.*, 2004; Arechavaleta *et al.*, 2005; Borges *et al.*, 2008). Many of these endemics are threatened, given their restricted distributions and the fragility of the habitat in which they occur.

Thus in common with many other oceanic islands and archipelagos, Madeira has a fauna and flora rich in endemic species. Apart from isolation, that has promoted independent evolution, variation in topography and local climate results in varying vegetation and a large diversity of habitat types. Six climatophilous vegetation complexes and three edaphilous vegetation complexes have been identified (Capelo *et al.*, 2004). The endemic flora of Madeira island (most notably the Laurel Forest, also known as Laurissilva) has a palaeoendemic origin, and consists of a surviving portion of the continental vegetation present in Europe in the late Tertiary, matched now only by an equivalent refuge in the Caucasus (Sjögren, 1972; Capelo *et al.* 2004). The largest area of pristine forest (*Clethro-Ocoteetum-foetentis*), with approximately 16143 ha (47% of the total forest area; SRARN, 2008), occurs in higher altitudes, particularly in the northern side of the island (Capelo *et al.*, 2004). This area of Laurel forest (SPA/SAC Laurissilva da Madeira) and the higher central peaks of Madeira Island (SAC Maciço Montanhoso Central) are crucial centres of endemic diversity, including several species of endemic terrestrial snails. These areas are very vulnerable either to climate change as well as human disturbance.

1.8. The Madeiran land snail fauna

Land molluscs play an important role in many ecosystems especially as detritivores feeding on dead plant material (Lydeard *et al.,* 2004; Seddon, 2008). Many have low mobility, low dispersal rates, and very narrow distributions, often confined to small areas with very specific habitat characteristics. If some of these are lost, they may find it very difficult to recolonise from refuge areas even when appropriate conditions are restored.

Madeira has a rich land snail fauna. In total, a complete bibliographic review (Abreu and Teixeira, 2008) lists 187 species and subspecies on Madeira itself (104 are endemics), with 104 on Porto Santo (89 are endemics) and 37 on the Desertas (31 are endemics). After the group of arthropods, mollucs represent the greatest proportions of endemics, and are underestimates of the natural state: some non-endemic *taxa* are present as a result of recent introductions. Many of these endemics have very restricted distributions, or have been found only rarely in scattered locations where the specific environmental conditions have not been recorded. The endemic fauna represents a unique set of colonisations from the mid-Tertiary onwards, augmented by local speciation within the islands (Waldén, 1983). There have been at least 20 colonisation events from Europe to the island of Madeira over the c. 5 Myr of its existence (Cameron and Cook, 1992, 2001), and it appears that the geological and climatic history of the island promoted non-adaptive radiation in which isolated populations occupying the same niche diverged to form new species (Cook, 2008).

In addition, there are suites of species adapted to particular habitats. Within the Laurel forest, there is little sign of any geographical pattern, but many species are known only from a few localities. In the drier coastal areas, and particularly in the south, the fauna is different from that of the Laurel forest, more influenced by non-endemic species, and with a clear geographical differentiation (Cook *et al.*, 1990; Cameron and Cook, 1992, 1997; Cook, 1996).

As in other islands, this fauna is very vulnerable to extinction; oceanic island land snails have the highest number of documented extinctions of any major taxonomic group (Van Bruggen, 1995; Lydeard *et al*., 2004). Like other invertebrates with low dispersal abilities, molluscs are, in many cases, the first to become extinct in response to habitat loss and disturbance, and this is often perceived as the major threat, although on some islands other than Madeira the activities of introduced predators are equally severe (Lydeard *et al*., 2004). Evidence from elsewhere shows that snails are particularly sensitive indicators of refugia in which favourable environments for wildlife have persisted for long periods (Moritz *et al.*, 2001). Despite losses from earlier human activity, the endemic snail fauna of Madeira has survived better than those on many other oceanic islands (Cameron and Cook, 2001; Lydeard *et al.*, 2004).

Nevertheless, the effects of habitat destruction on Madeira can be seen both in the fossil record spanning the first human colonisation of Madeira (Goodfriend *et al*., 1994) and in the disappearance of species from localities around Funchal known to 19th century observers (Wollaston, 1878; Seddon, 2008). In August 2010, much of the highest-altitude Laurissilva was devastated by fires. These have extended the effects of this destruction. Conservation policies have therefore concentrated on the protection of native habitats.

Climate change can present an additional threat. The lack of information about the real impacts of climate changes on this group (neglected by IUCN assessments and the European Red List of Non-marine Molluscs (Cuttelod *et al*., 2011)), in addition to their exclusion from conservation efforts and biodiversity monitoring, presents a challenge for conservation planning.

1.9. The conservation of Madeiran snails

Although not all Madeiran species have been assessed, 57 endemic species fall into one of the “endangered” categories defined by the International Union for the Conservation of Nature (IUCN, 2013). The IUCN Red List of Threatened Species is widely recognized as the most comprehensive, objective global approach for evaluating the conservation status of plant and animal species at risk of extinction (Lamoreux *et al.*, 2003; IUCN, 2013). With a number of objective criteria, the IUCN Red List was meant to be applicable to the majority of the described species, although this has been questioned (Cardoso *et al.*, 2011). However, the quality of available information for invertebrates is generally lower than for vertebrates (IUCN, 2013), neglecting small species with restricted distribution and low dispersal abilities, which constitute the vast majority of the planet's biota. In particular, data relating to the monitoring of population size and fluctuations is not usually available, and would, in most cases, be impossible to obtain within feasible costs. Therefore, the most threatened invertebrate species are commonly excluded from conservation efforts and biodiversity monitoring (Martín *et al.*, 2010; Cardoso *et al.*, 2011).

The conservation status of endemic Madeiran molluscs has not been evaluated, according to IUCN Red List guidelines, since 2011 (IUCN, 2013). The list includes assessments of 132 species of terrestrial land snails from the Madeiran archipelago, almost half being threatened (19 as *Critically Endangered* (CR), 11 as *Endangered* (EN), 27 as *Vulnerable* (VU), 12 as *Near Threatened* (NT), as 54 *Least Concern* (LC), 7 as *Data Deficient* (DD) and 2 as *Extinct* (EX)), invariably with unknown population trends.

In general, the effects of future climate change are neglected in IUCN assessments, as the time-frame for IUCN assessments is usually of 10 years into the past or future while climate change projections are made up to 100 years. These are likely to be greatest where the ranges of species are smallest, and associated with habitats at the climatic limits in the region. Studies concerning the impacts of climate change on global biodiversity have increased in recent years, and the evidence suggests that the biological and ecological responses of a wide range of life forms are complex and require progressively more advanced tools in the creation of action plans and other conservation strategies (IPCC, 2007a). This information can be used to determine biodiversity vulnerability as a basis for prioritizing species and defining management strategies (Kareiva *et al.,* 2008).

For all these reasons, the endemic snail fauna of Madeira needs study using modern techniques incorporating models of climate change. Such a study can provide a sensitive instrument for monitoring change and help to identify appropriate conservation actions to preserve the unique character of the fauna (Seddon, 2008). As a start, this study therefore considers the snail fauna of the Laurel forests on Madeira. This fauna includes 46 molluscan *taxa*, 29 of them endemic (Abreu and Teixeira, 2008). The endemic fauna is dominated by thin-shelled or small species suited to the cool, damp and often calcium-deficient environment within the forests (Sjögren, 1972; Cameron and Cook, 1997), and many are known from only a handful of sites.

1.10. Main objectives

The proposed study aims firstly to re-evaluate the conservation status and population trends of several mollusc species, assembling data from bibliographic research, expert consulting, *in loco* sampling and habitat suitability modelling.

In order to properly understand the impact of climate on these vulnerable *taxa* and provide preliminary data for future studies concerning the archipelago's malacofauna, this thesis aims to conduct a preliminary analysis of the climatic tolerance of these species and their possible responses to future climatic change. This analysis will evaluate the predicted trends of various native species of terrestrial molluscs facing a changing climate scenario for Madeira Island.

In the present study we aim to:

1. Map the current distribution of selected Laurel forest land snail species and to evaluate their present conservation status;
2. Identify the potential distribution areas of the selected species using predictive models, and to compare them with known distributions, according to their habitat and niche preferences;
3. Evaluate the impact of climate change on the selected species, using the models developed for the previous objective.

2. MATERIALS AND METHODS

2.1. Study area

The Madeira archipelago is located in the Atlantic Ocean, approximately 1000 km from Sagres, on the Portuguese coast, and 500 km from Africa, between 32º24’ and 33º07’ north and 16º16’ and 17º16’ west. It is composed of three main groups of islands: Madeira, Porto Santo and the Desertas, occupying a total area of 740 km^2 (Figure 1).

Figure 1: Map of the Madeira Island and Desertas, with Natura 2000 network and Madeira Natural Park areas.

On the island of Madeira itself, 75% of the island is subject to some degree of legal protection; and seven *Special Areas of Conservation* (SAC) and two *Special Protection Areas* (SPA) are designated within the Natura 2000 framework (Figure 2). Protection of threatened species and habitats is also provided for by *European Union Species and Habitats Directive* (EUSHD) (together with the *Birds Directive*), which requires member states to monitor and maintain favourable conservation status for listed species.

I therefore restricted the study area of this work to the Laurel forest (*SPA/SAC Laurissilva da Madeira*) and central peaks of Madeira Island (*SAC Maciço Montanhoso Central*). These protected areas contain the most humid and highest habitats, which are expected to show the greatest changes under anticipated climate change. It is also in these areas that a significant number of endemic terrestrial snails survive.

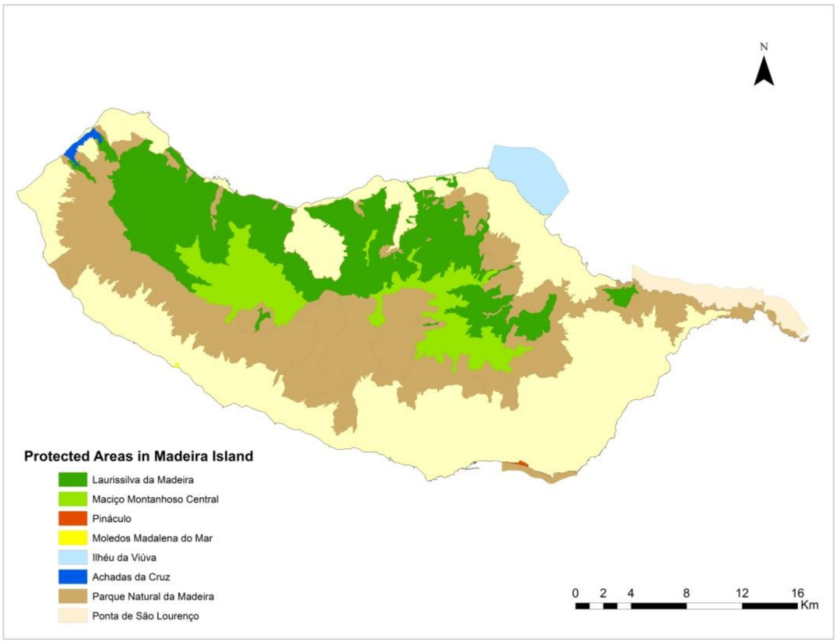

Figure 2: Map of Protected Areas in Madeira Island.

2.2. Preliminary data compilation

Thirty-six *taxa* of endemic snails are recorded exclusively in the target areas (Table 1, Annex 1). Their distribution data were collected from Madeira's Biodiversity Database (BIOBASE), a powerful and updated database, designed to provide coherent information, validated and georeferenced, for managers and policy makers in the field of conservation and biodiversity. Species' distribution records, referenced to the UTM grid of 500x500 m, were exported to an *ESRI shapefile*.

2.3. Sampling

Although Madeira´s Biodiversity Database (BIOBASE) comprises a significant fraction of information about the distribution of Madeira Island's malacofauna, some areas have a very small amount of recorded data. In order to complement the information about the distribution and current conservation status of Madeira's land snails, the first stage of this work comprised the identification and sampling of 15 sites in Laurel forest and alpine habitats.

Priority sampling areas were determined through the analysis of the potential distribution sites of target species (Teixeira, 2009), the available information of species ecological requirements and the accessibility of the sampling stations. In order to cover both protected areas and fill the distribution gaps, a total of 15 sites were surveyed (Figure 3).

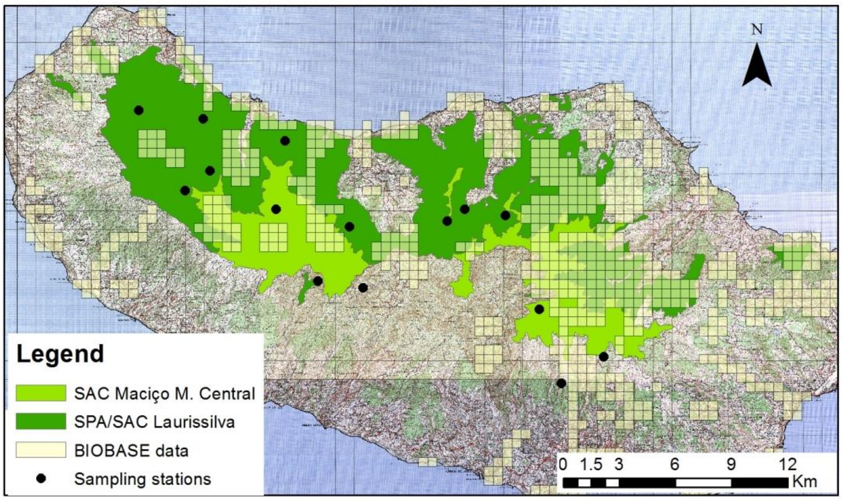

Figure 3: BIOBASE data distribution and sampling stations within the study area.

These stations stretched from near Porto Moniz, in the western part of the island, to central peaks in Maciço Montanhoso Central. Fieldwork was done between October and June, when the weather is more suitable (cool and moist), increasing the probability of detecting living animals. To evaluate the presence of the target species in the area, land snails and semi-slugs were surveyed on squares of 30x30m (one square for each station), by two people, for about one hour (Cameron and Cook, 1997).

Species identification was made based on external characters of the shell and follows the nomenclature of Bank *et al.* (2002).

2.4. Climate data and scenarios

Oceanic islands often have limited meteorological information, and global circulation models (GCM), are not enough to understand the regional scale of the impact of climate change on biodiversity. To model species' distributions under present and future climate, we used climate data produced within project CLIMAAT II (Santos and Aguiar, 2006), based on the regionalization of the global circulation Hadley Centre Coupled Model (HadCM3), using a simple thermodynamic model, CIELO (Portuguese acronym for "Insular Climate at Local Scale"; Azevedo, 1996; Miranda *et al.*, 2006).

CLIMAAT data were produced based on IPCC Special Report Emission Scenarios (IPCC, 2000), using the A2 and B2 greenhouse gases concentration scenarios, and climate scenarios for 1961-1990 (control period), 2040-2069 and 2070-2099 were produced. Predicted climate scenarios for the control period were validated with climatic cartography produced by interpolation of sampled data at several meteorological stations

(Cruz *et al.*, 2008). CLIMAAT II data are currently available at a resolution of 1 km^2 (Santos and Aguiar, 2006).

For each species, we considered the A2 and B2 emission scenarios. The A2 emission scenario describes a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines with a fourfold increase in CO2 levels with respect to their 1990 levels by the year 2100. The B2 scenario is based on a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development, assuming a doubling in CO_2 emission by the year 2100 (IPCC, 2007a).

Ten bioclimatic/geographic variables were selected on a first step, in order to represent biologically meaningful measures for characterizing species distributions: annual mean, maximum and minimum temperature, precipitation, relative humidity and altimetry (Table 2, Annex 1).

Correlation between variables was analysed using ENM Tools (www.ENMTools.com; Warren *et al.*, 2010). Annual maximum temperature, annual minimum precipitation and annual minimum relative humidity were the selected variables to run the model, for each period. These were thought *a priori* to be the limiting factors to the distribution of snails, highly vulnerable to high temperatures and low humidity levels and because these are thought to be the factors that will change to values outside their current ranges in the future. All other variables were highly correlated with these and were removed from the model (in all cases $r > 0.67$). All the environmental data were converted to 1000x1000m grid cells and then into ASCII files, with *ArcGIS 10.0* geoprocessing tools.

2.5. Habitat data and future changes

Besides suitable climate, land snail distribution is influenced by many other variables. Although there is no clear information about niche requirements, target species ranges are clearly dependent on Laurel forest or alpine areas.

Future projections regarding land use changes are missing for Madeira archipelago. In order to add some information on habitat future changes, I have used data for three classes of vegetation: natural forest, natural shrub areas and natural herbaceous vegetation, from COSRAM 2007 (Figure 4).

In addition to the above mentioned climatic variables, and considering that vegetation is highly influenced by edaphic variables, I’ve also included soil type, slope and geology

(Table 2, Annex 1), considering that these non-climatic variables would remain constant until the end of the century.

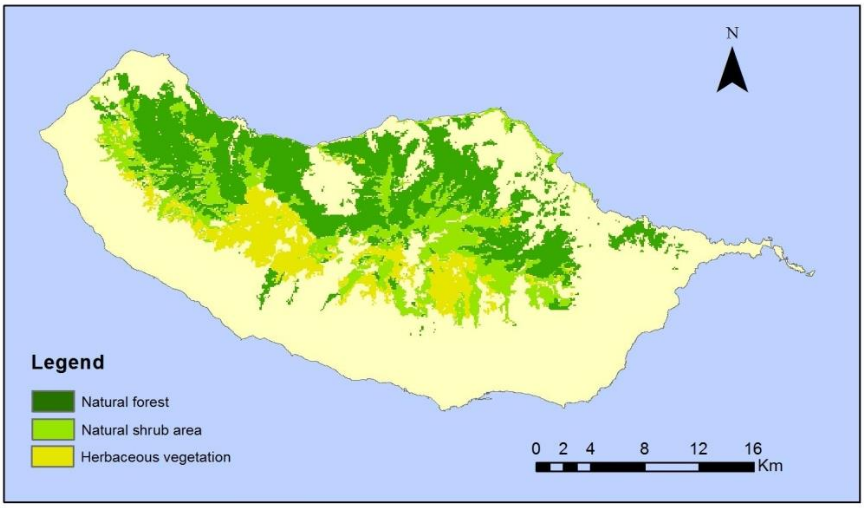

Figure 4: Distribution of natural forest, natural shrub areas and natural herbaceous vegetation in Madeira Island, according to land use map COSRAM 2007.

2.6. Species distribution modelling under climate change only

To identify the species' current potential distribution areas and predict changes in species distributions as a result of climate change only MaxEnt version 3.3.3k was used (see Phillips *et al.*, 2004, 2006; available for free at http://www.cs.princeton.edu/ Schapire~/MaxEnt/). This machine learning method is based on maximum entropy algorithm for predicting species distribution models when only presence data are available (Elith *et al.*, 2006).

MaxEnt software has been widely used on habitat suitability modelling (Elith *et al.*, 2006; Ortega-Huerta and Peterson, 2008; Kumar and Stohlgren, 2009; Teixeira, 2009) and has been shown to produce useful results even with small sample sizes (Hernandez *et al.*, 2006; Papes and Gaubert 2007; Lobo *et al.*, 2008; Benito *et al.* 2009; Elith and Leathwick, 2009), and when projecting models into novel environments and future scenarios (Hijmans and Graham, 2006; Kearney *et al.*, 2010; Ponce-Reyes *et al.*, 2012).

MaxEnt calculates the observed association between species and environmental layers under the constraint that the expected value of each environmental variable under the estimated distribution must be similar to its observed average over species occurrence data (Phillips *et al.*, 2006; Phillips and Dudik, 2008). This software has the additional advantage of allowing the use of continuous and categorical variables simultaneously.

MaxEnt requires point locality data. Species distribution information was converted into single geographical positions of the selected species' distribution, by estimation of the centroid of each cell. To prevent points arising in the sea from this process, border grid cells were "clipped" to the Madeira Island coastline *shapefile*. These operations were performed with *Python* scripting language and a joint *Arc ToolBox* was created (Figure 1, Annex 2). Once the centroids were shaped, a second script and a toolbox were created in order to attribute coordinates to each point (Figure 2, Annex 2).

For each species, models were ran using the default settings which have been adjusted to perform well across a multiplicity of organisms and regions (Phillips and Dudik, 2008), except for the iterations set for 1000 (from a default of 5000).

To evaluate model performance, metrics of model fit are needed (Liu *et al.*, 2011). Area under the receiver-operator curve (AUC) has been broadly used for model evaluation and is part of MaxEnt output (Elith *et al.*, 2006). The receiver operating characteristic (ROC) analysis is based in a plot of "sensitivity" (how the data correctly predicts presence) and "1–specificity" (measure of correctly predicted absences; Fielding and Bell, 1997). To develop the ROC plot, 75% of the data were selected for training data and 25% were used for test data (Pearson *et al.*, 2007). AUC is interpreted as the probability that a randomly chosen presence location is ranked higher than a randomly chosen background point (Merow *et al.*, 2013), generating a single measure of model performance, providing information on the efficacy of the model (i.e., AUC: >0.9 = Very good; AUC: 0.7–0.9 = good, AUC: <0.7 = uninformative; Swets, 1988).

Modelling outputs were exported in ASCII file, as a continuous prediction of site suitability for each species, ranging from 0 to 1. Grid cells with values closer to 1 correspond to higher site suitability for species distribution (Phillips *et al.*, 2006).

Although continuous site or habitat suitability maps express more information (Vaughan and Ormerod, 2005), binary output maps, using a probability threshold for conversion to presence/absence have been used in a wide range of studies such as biodiversity assessments, protected areas identification and climate change impact assessments (Lobo *et al.*, 2008; Rebelo and Jones, 2010). This "cut-off value" should not be chosen arbitrarily (Hernandez *et al.*, 2006), and, whenever presence and absence data are available, several methods for selecting a threshold to transform continuous values into binary predictions can be used (Liu *et al.*, 2005; Jiménez-Valverde and Lobo, 2007; Pearson, 2007; Liu *et al.*, 2013). However, only presence data are available on Madeiran terrestrial snails.

According to recent studies on threshold selection with presence-only data (Liu *et al.*, 2013), Max SSS (which is based on maximizing the sum of sensitivity and specificity) produces higher sensitivity in most cases and higher true skill statistic (TSS). This criterion was used in producing the binary maps.

2.7. Habitat distribution modelling

There are no estimates of climate change impacts on land use or vegetation for Madeira. To model the species' current potential distribution areas and predict changes in species distributions as a result of both climate and habitat change, we first had to model the future distribution of the different habitat types, assuming that they currently occupy their entire historical climatic range (even if the spatial distribution is reduced in relation with the original). In order to understand and overview the major trends of these natural habitats as a result of climate change, we again used MaxEnt. Three classes of vegetation available in *shapefile* format were converted to equidistant points (500 m). Single geographical positions of vegetation classes were extracted and exported as CSV format. For each class, we ran the model using the default settings (10 replicates), except for the iterations (1000) and applying threshold rule Max SSS. The model outputs were processed according to the description in "Post-modelling processing" section (Annex 3, Figures 1-3), and then converted to ASCII files.

2.8. Species distribution modelling under climate and habitat change

A new analysis was made in order to evaluate changes in species distribution under both climate and habitat/vegetation type change scenarios. In addition to climate (annual maximum temperature, annual minimum precipitation and annual minimum relative humidity) and habitat (natural forest, natural shrub areas and natural herbaceous vegetation), geographical variables (latitude and longitude) were added to the model, so that the orography of the region with consequent barriers to dispersal were taken into account. In fact, complex orography was previously found critical for the distribution of snails (Teixeira, 2009) and other *taxa* such as beetles (Boieiro *et al*., 2013).

For each species, we ran the models using the default settings, except for the iterations set for 1000. Model evaluation was performed by AUC analysis and individual binary maps were created using the same methodology as described for species modelling under climate change.

2.9. Post-modelling processing

MaxEnt produced ten ASCII continuous maps (replicates), for each species in five modelled scenarios (current (1990), A2 and B2 for both 2040-2069 and 2070-2099), and for each of two models, with and without habitat change (Figure 5). *Python* scripts converted remaining single species datasets into *Raster* (Figure 3, Annex 2), and then into single binary maps, using their Max SSS as threshold.

As particular thresholds are specific to single produced maps, single binary maps were created based in the assumption that where presence is indicated in at least 6 of the 10 replicates, the species was considered as present. On the other hand, if the species was present in 5 or less of the 10 replicates, it was considered as absent. This methodology was performed by scripts for each studied species (Figure 4 and Figure 5, Annex 2).

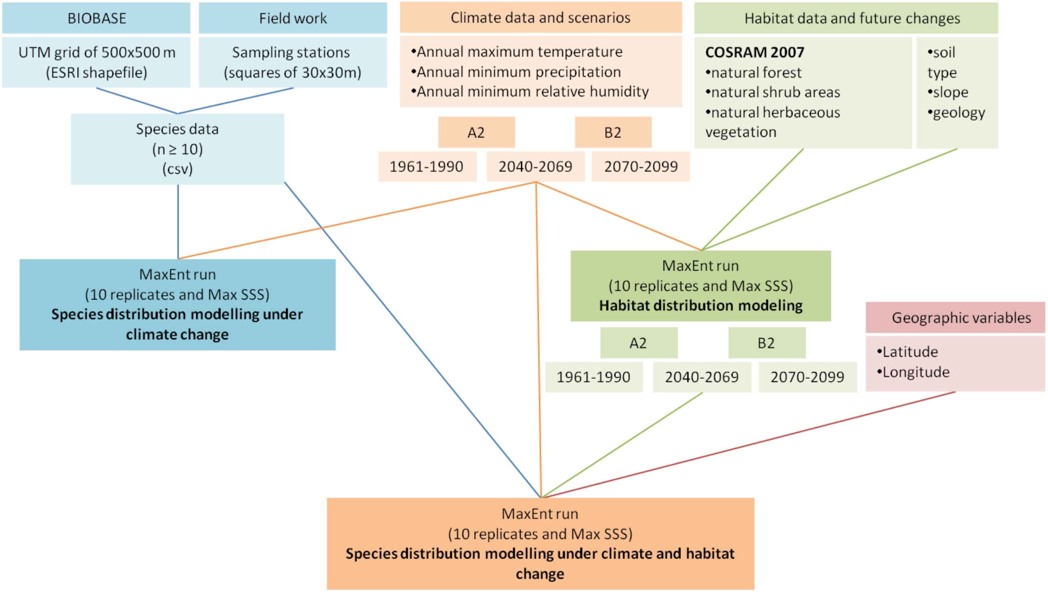

Figure 5: Flowchart of modelling methodology.

2.10. Changes in biodiversity descriptors

Studies concerning beta diversity have been widely used to understand the two distinct processes that shape communities and their differences: species replacement (or turnover) and species loss (or gain) (Williams, 1996; Williams *et al.*, 1999; Lennon *et al.*, 2001; Baselga, 2007, 2010; Carvalho *et al.*, 2012, 2013). Beta diversity between sites or points in time can be a result of a wide range of mechanisms, such as extinction, colonization or dispersal limitation (Urban *et al.*, 2006; Ulrich *et al.*, 2009). Within this study, the main interest was in understanding how land snails communities react to climate change, through the identification of the relative roles of species replacement and richness differences (beta diversity patterns), amongst different climatic scenarios and temporal periods.

Recently, some authors have introduced this framework in order to evaluate beta diversity as a result of climate change (Dortel *et al.*, 2013).

In nature, processes driving community composition can be combined in an infinite number of ways, leading to complex patterns of community dissimilarity (Carvalho *et al.*, 2013). Therefore, a means of decomposing measures of beta diversity into single fractions of replacement and richness differences is required. In the last years, several authors have discussed different ways of partitioning beta diversity (Koleff *et al.*, 2003); however none of these studies provided a comprehensive and unified framework (Carvalho *et al.*, 2013).

A novel approach to beta diversity partitioning was recently proposed (Carvalho *et al.*, 2012, 2013). This framework is based on partitioning dissimilarity in terms of the Jaccard index (β_{cc}) into two additive fractions dissimilarity due to species replacement, (β_{-3}) plus dissimilarity due to richness differences (β_{rich}):

$$\beta_{cc} = \beta_{-3} + \beta_{rich}$$

As suggested by Carvalho *et al.* (2013), we followed the standard notation (Koleff *et al.*, 2003), where *a* is the number of species present in both periods, *b* is the number of species exclusive to the first period and *c* is the number of species exclusive to the second period (Figure 6).

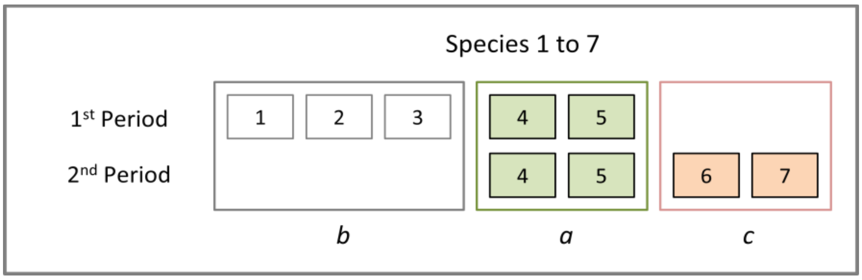

Figure 6: Matching/mismatching components between two periods: *a* is the number of species present in both periods, *b* is the number of species exclusive to the first period and *c* is the number of species exclusive to the second period. Adapted from Carvalho *et al.* (2012).

The total number of species in the system (gamma diversity) is given by the sum of species number ($a + b + c$). Beta diversity, obtained by Jaccard dissimilarity measure (β_{cc}; complementary measure of Colwell and Coddington (1994)), is the proportion of total compositional differences between two periods in relation to the total number of recorded species, and it is expressed by the following function:

$$\beta_{cc} = \frac{b + c}{a + b + c}$$

Species replacement is taken as the substitution of n species in one period to the same number of species in a second period. Consequently, the number of substitutions between two periods is given by the minimum number of exclusive species $(2 \times \min(b, c))$ in relation to the total number of recorded species $(a + b + c)$, as suggested by the measure β_{-3} of Williams (1996), modified by Cardoso *et al.* (2009):

$$\beta_{-3} = 2 \times \frac{\min(b, c)}{a + b + c}$$

Species richness for each period is given by expressions $b + a$ and $c + a$, in proportion to the total of number of species recorded $(a + b + c)$. The absolute difference between species richness of two periods is given by the following equation:

$$\beta_{rich} = \frac{|(\mathrm{b} + \mathrm{a}) - (\mathrm{c} - \mathrm{a})|}{\mathrm{a} + \mathrm{b} + \mathrm{c}} = \frac{|\mathrm{b} - \mathrm{c}|}{\mathrm{a} + \mathrm{b} + \mathrm{c}}$$

This new methodology characterizes species replacement and species loss (or gain) processes in an ecologically and mathematically significant approach (Carvalho *et al.*, 2012).

Species' gain (component c), loss (component b) and maintenance (component a) were calculated for each pairwise combination of the three analysed periods (present vs. 2040-69; 2040-2069 vs. 2070-99; present vs. 2070-99), according to A2 and B2 scenarios with and without habitat change data. With the aim of converting single species predictions into "community" maps, we overlapped each one of individual predictions. Beta diversity patterns were extracted, with *ArGIS Raster Calculator Tool*, in order to analyse species richness difference and replacement in each scenario (Table 1, Annex 2). Indexes were rescaled to a 0-100 range.

3. RESULTS

3.1. Sampling data

Twenty species of land snails and three semi-slugs were collected during the fieldwork. Twelve of these species were among those chosen for this study (Table 1).

ID	Species	IUCN conservation status	Population trend	Sampling
1	*Actinella actinophora*	Vulnerable	unknown	+
2	*Actinella armitageana*	Vulnerable	unknown	+
3	*Actinella arridens*	Critically Endangered	unknown	-
4	*Actinella carinofausta*	Endangered	unknown	-
5	*Actinella fausta*	Least Concern	unknown	-
6	*Boettgeria crispa*	Near Threatened	stable	+
7	*Caseolus calvus*	Endangered	unknown	-
8	*Craspedopoma lyonnetianum*	Vulnerable	unknown	-
9	*Craspedopoma mucronatum*	Least Concern	stable	+
10	*Craspedopoma neritoides*	Least Concern	unknown	+
11	*Craspedopoma trochoideum*	Least Concern	stable	+
12	*Geomitra delphinuloides*	Critically Endangered	unknown	-
13	*Geomitra tiarella*	Endangered	unknown	-
14	*Hemilauria limnaeana*	Least Concern	stable	-
15	*Lauria fanalensis*	Least Concern	stable	-
16	*Leiostyla arborea*	Vulnerable	unknown	-
17	*Leiostyla cassida*	Critically Endangered	decreasing	-
18	*Leiostyla cassidula*	Critically Endangered	unknown	-
19	*Leiostyla cheilogona*	Least Concern	stable	-
20	*Leiostyla colvillei*	Vulnerable	unknown	-
21	*Leiostyla concinna*	Endangered	unknown	-
22	*Leiostyla falknerorum*	Endangered	unknown	-
23	*Leiostyla heterodon*	Vulnerable	unknown	-
24	*Leiostyla irrigua*	Least Concern	stable	-
25	*Leiostyla laurinea*	Vulnerable	unknown	-
26	*Leiostyla loweana*	Least Concern	stable	-
27	*Leiostyla sphinctostoma*	Least Concern	stable	-
28	*Leiostyla vincta vincta*	Least Concern	stable	-
29	*Leiostyla vincta watsoniana*			-
30	*Leptaxis furva*	Vulnerable	unknown	+
31	*Leptaxis membranacea*	Least Concern	unknown	+
32	*Plutonia albopalliata*	Vulnerable	unknown	-

33	*Plutonia behnii*	Least Concern	stable	-
34	*Plutonia marcida*	Least Concern	stable	+
35	*Plutonia nitida*	Least Concern	stable	+
36	*Plutonia ruivensis*	Least Concern	stable	+

Table 1: List of target species, IUCN conservation status, population trend and occurrence within sampling stations.

Twenty seven new records were added to the BIOBASE data. Specimens from Hygromiidae were the most frequent in sampled stations (4 species), followed by Craspedopomatidae and Vitrinidae, with 3 species each. Only one species of Clausiliidae was detected.

Fieldwork provided 19 new records for 11 of the target species. Sampling near Ribeira da Janela identified a new location for *Boettgeria crispa*, and new locations for *Craspedopoma trochoideum*, *Craspedopoma neritoides* and *Craspedopoma mucronatum* were identified in the surroundings of known areas. *Leptaxis furva* expanded its range to the western part of the island. *Leptaxis membranacea*, *Plutonia marcida*, *Plutonia nitida* and *Plutonia ruivensis* were also found in sites near their known distribution.

3.2. Modelling land snails' distribution under climate and habitat change scenarios

Two datasets were modelled for 31 endemic land snails: a) under current and future climate scenarios (A2 and B2 scenarios); and b) under current and future climate scenarios and changes in vegetation, further considering the current geographical boundaries. *Actinella carinofausta*, *Caseolus calvus*, *Geomitra delphinuloides*, *Hemilauria limnaeana* and *Leiostyla cassidula*, were excluded from our analysis, due to low number of records ($n \leq 10$), making any models most probably unreliable.

The majority of the models (53.23%) were considered very good (AUC > 0.90) and the remaining 46.77% were classified as good (0.70 < AUC < 0.90; Table 1, Annex 4).

The importance of climatic/habitat/geographical variables was evaluated by jackknife analysis from MAXENT outputs (Table 2 and Table 3, Annex 4). When considering climatic variables only, all three variables were the main delimiters of the envelope for roughly the same number of species (Figure 7). The second analysis, including vegetation changes and geographical variables, suggests a different pattern with longitude and the existence of natural forest representing the most important features in species distribution for most species (Figure 8). In this case, climatic variables seem to be less important than habitat and spatial variables.

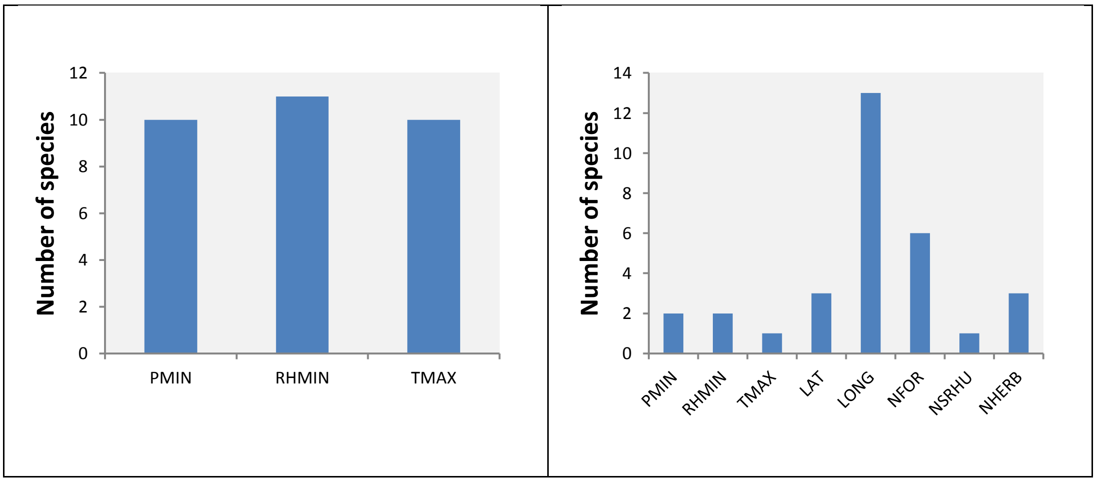

Figure 7 and 8: Relative importance of environmental variables in species' distribution, for modelled scenarios (TMAX – maximum temperature; PMIN – minimum precipitation; RHMIN – minimum relative humidity; NFOR – natural forest; NSHRU – natural shrub; NHERB – herbaceous vegetation; LAT - latitude; and LONG - longitude).

3.3. Changes in species ranges – future forecasted distributions under climate and habitat change

Important changes in distribution emerged for both scenarios (A2 and B2). Our model projects a multiplicity of potential responses to climate and habitat change, ranging from the loss of suitable areas to a significant increase in areas with appropriate climate conditions. The distribution of current and future suitable climate and vegetation for modelled species is shown ordered by family.

3.3.1. Craspedopomatidae

This is the only group of operculate snails in the Madeiran fauna. The family was present in Europe in the Tertiary, but is now restricted to a palaeoendemic distribution onthe archipelagos of Madeira, Azores and Canaries.

Craspedopoma mucronatum is the only widespread species of the genus in Madeira Island. All the remaining species are range-restricted, often extremely localised. *C. mucronatum* is found in habitats with high humidity, in damp wooded areas near the soil and amongst mosses and on rocky ledges in ravines. Both climate and climate/habitat/geography models (hereafter full models) identified several potential areas for *C. mucronatum* occurrence (Figure 9). According to the climate model, future projections under both scenarios suggest a decrease in its distribution areas (< 25% of the current modelled range in A2 scenario and < 5% in B2). The full model suggests that the distribution of *Craspedopoma mucronatum* is mainly influenced by the presence of forested areas, followed by geographic variables (longitude and latitude). Future projections under both scenarios suggest a decrease in suitable areas (from 10% in B2 up to 30% in A2).

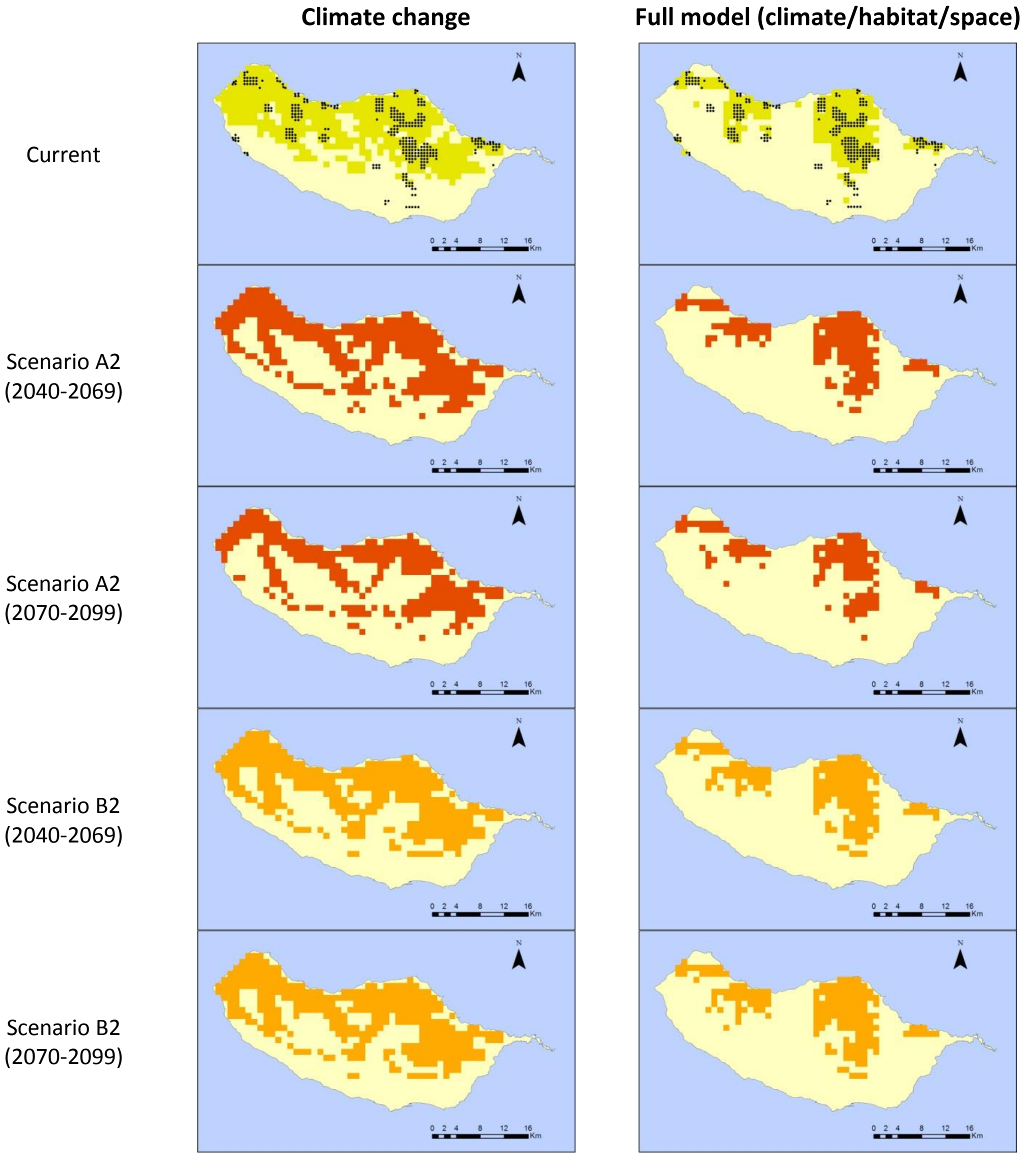

Figure 9: Predictive distribution maps for *Craspedopoma mucronatum*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

With a similar distribution pattern, *Craspedopoma neritoides* and *Craspedopoma troichoideum* occur from low to intermediate elevations, in the north side of the island. These species are often found at damp shaded forest areas, amongst leaf-litter, mosses and wet grass. Our climate model suggests wider potential areas for *C. neritoides* (Figure 10) and *C. troichoideum* (Figure 11), from intermediate elevations to the north coast. Influenced by temperature and relative humidity, both models suggest a clear positive tendency on suitable climate areas for *C. neritoides* (around 30%) and *C. troichoideum* (higher than 100%).

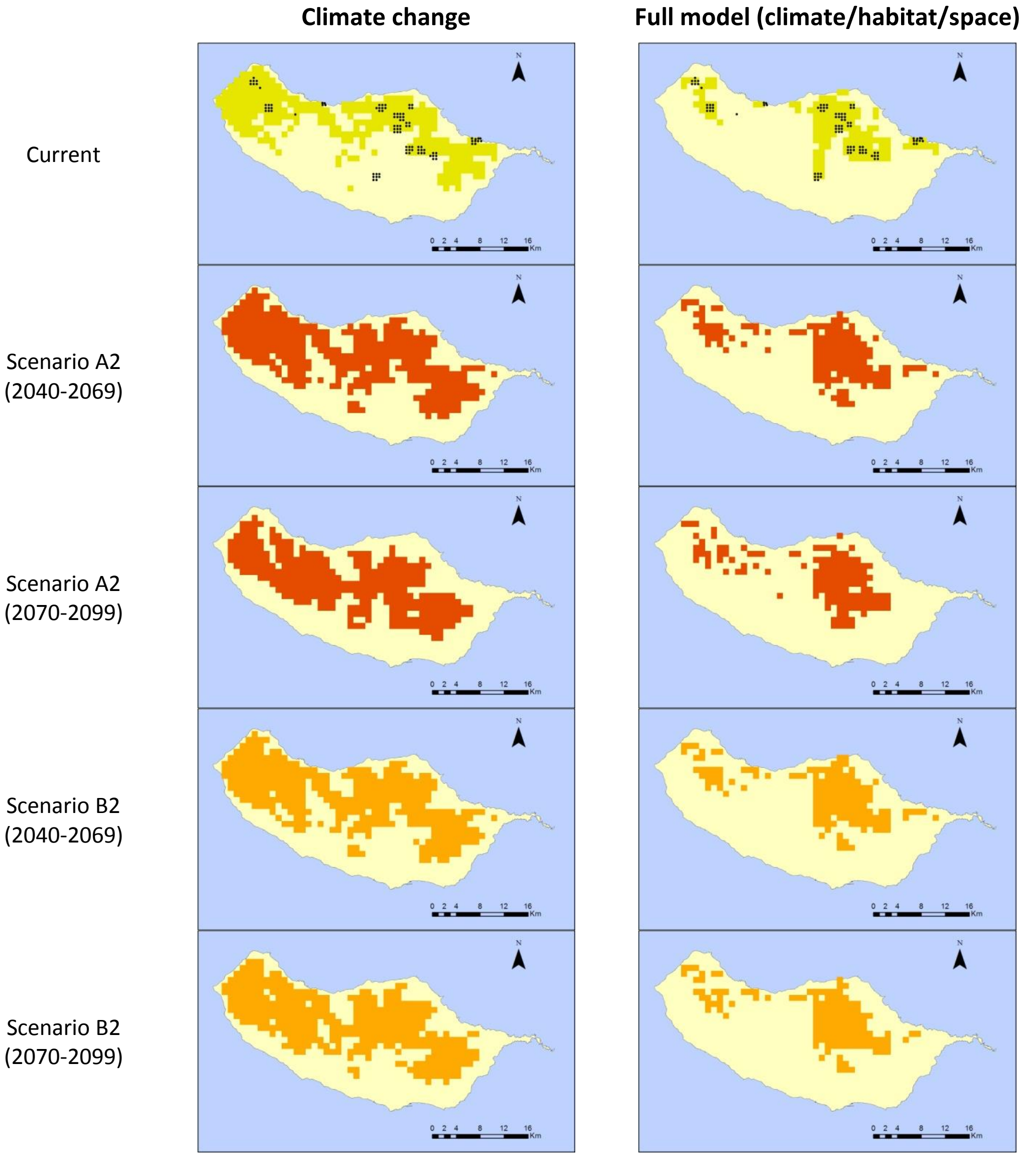

Figure 10: Predictive distribution maps for *Craspedopoma neritoides*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

As a result of their association to Laurel forest, *Craspedopoma neritoides* and *Craspedopoma troichoideum* range is highly influenced by the presence of forested areas, which is also predicted to increase, both in A2 and B2 scenarios (Figure 1, Annex 3).

Although both species demonstrate similar habitat requirements and positive trends, the full model suggest different changes in suitable areas for *C. neritoides* (expansion up to 10% of the current distribution) and *C. troichoideum* (expansion between 70% (B2) and 90% (A2) from current suitable areas).

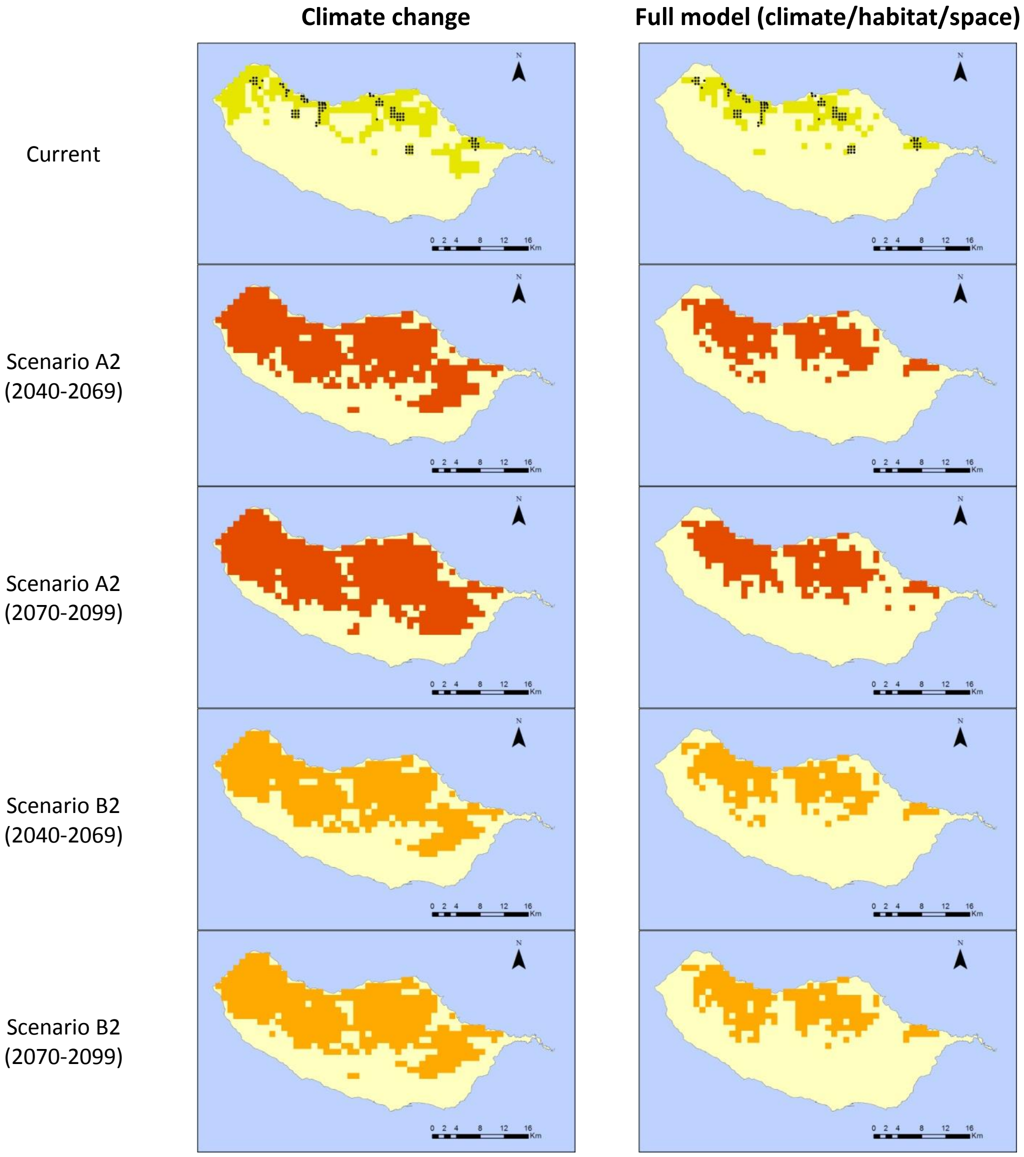

Figure 11: Predictive distribution maps for *Craspedopoma trochoideum*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Craspedopoma lyonetianum is mainly found in the Laurel forest in the central part of the island. Like the other *Craspedopoma* species, it is found in humid leaf-litter, mosses, soil and at the base of tall crags. With a low number of known localities, our model suggests new potential distribution sites for *C. lyonetianum*, mainly in the central part of the island (Figure 12).

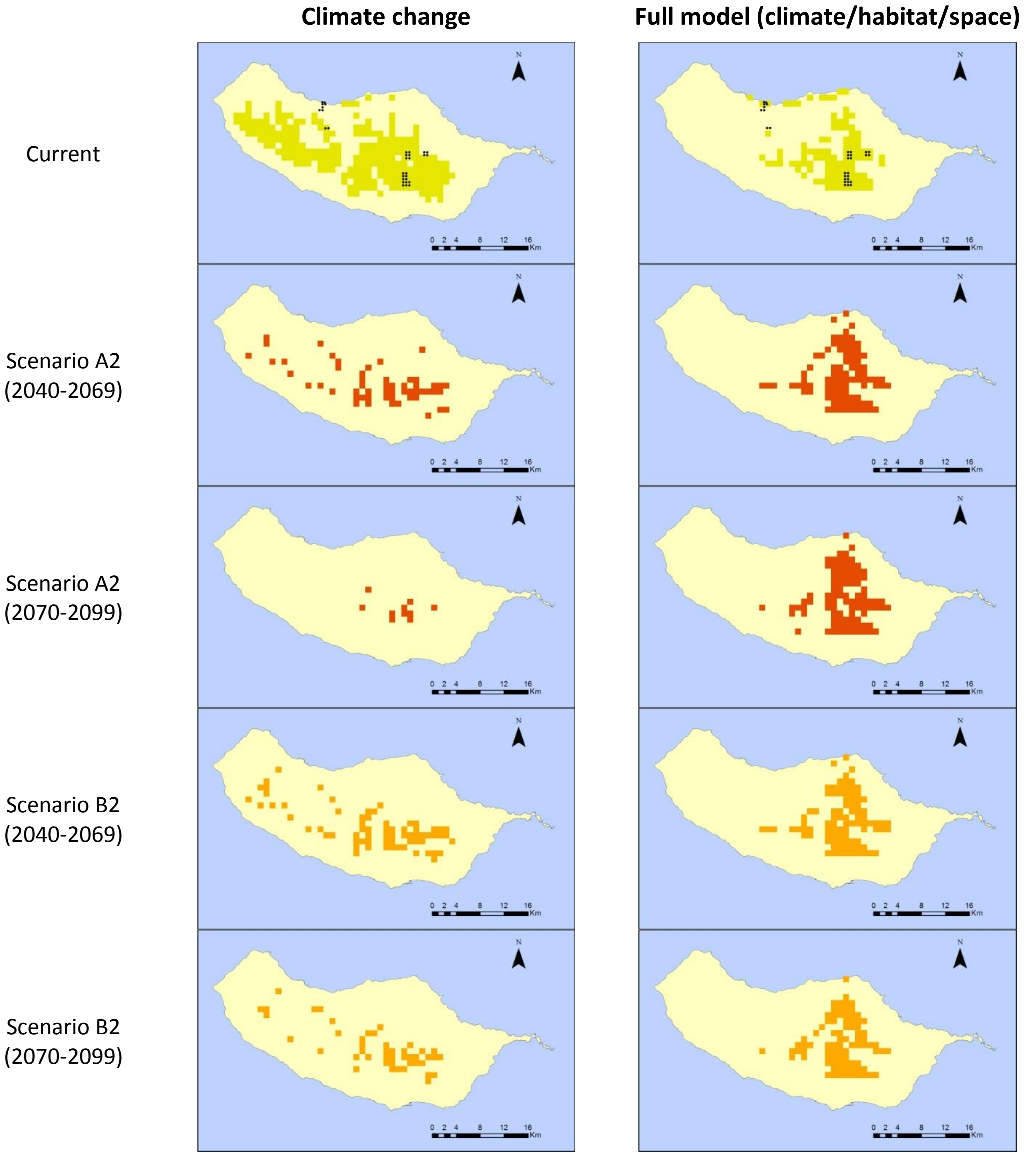

Figure 12: Predictive distribution maps for *Craspedopoma lyonnetianum*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Future scenarios under climate changes seem extreme, with the continuous loss of areas with suitable conditions for *C. lyonetianum*, both in A2 (up to 77.69% for 2040-69 period and 95.87% for 2070-2099) and B2 scenarios (up to 71.90% for 2040-69 period and 81.40% for 2070-2099). According to the full model, *C. lyonetianum* distribution is influenced by longitude, presence of herbaceous vegetation, presence of forest and latitude. The inclusion of habitat and geographic variables leads to a less catastrophic scenario, suggesting a slight decrease of suitable areas, both in A2 and B2 storylines, from 10 to 20%.

3.3.2. Lauriidae

On Madeira this family encloses *Lauria*, *Hemilauria* and *Leiostyla*, each *genera* with different distribution patterns and habitat requirements. *Lauria fanalensis* is found on ferns, moss and lichens at intermediate elevations within Laurel forest. According to the climate model, species' distribution is highly influenced by relative humidity and precipitation; and further climatically suitable areas were identified (Figure 13). Both A2 and B2 scenarios suggest a reduction in future suitable area for *L. fanalensis* (nearly 30% in both scenarios). Our full model identified relative humidity, precipitation and latitude as the main variables that influence *L. fanalensis* occurrence. New suitable sites were identified in A2 and B2 scenarios, suggesting the potential expansion of species distribution (up to 50% in A2 scenario).

Twelve IUCN listed *Leiostyla* species' occur in Laurel forest and summit areas. *Leiostyla arborea* is an arboreal species living mainly on the trunk of Laurel trees and on mosses. Mostly found at high elevations in the central area of Madeira, its distribution is very restricted. Climate modelling identified potential areas at intermediate and high elevation, mostly in the western and central part of the island (Figure 14). Future trends suggest a progressive reduction of suitable areas, especially alarming in the A2 scenario, with loss reaching up to 40%. As a result of its narrow distribution and in addition to precipitation, our full model identified longitude as the variable that contributes the most to *L. arborea* distribution range. Current modelling identified potential areas at intermediate and high elevations around known areas. Future trends, under climatic scenarios, suggest positive trends in future suitable areas (between 15% in B2 and 25% in A2).

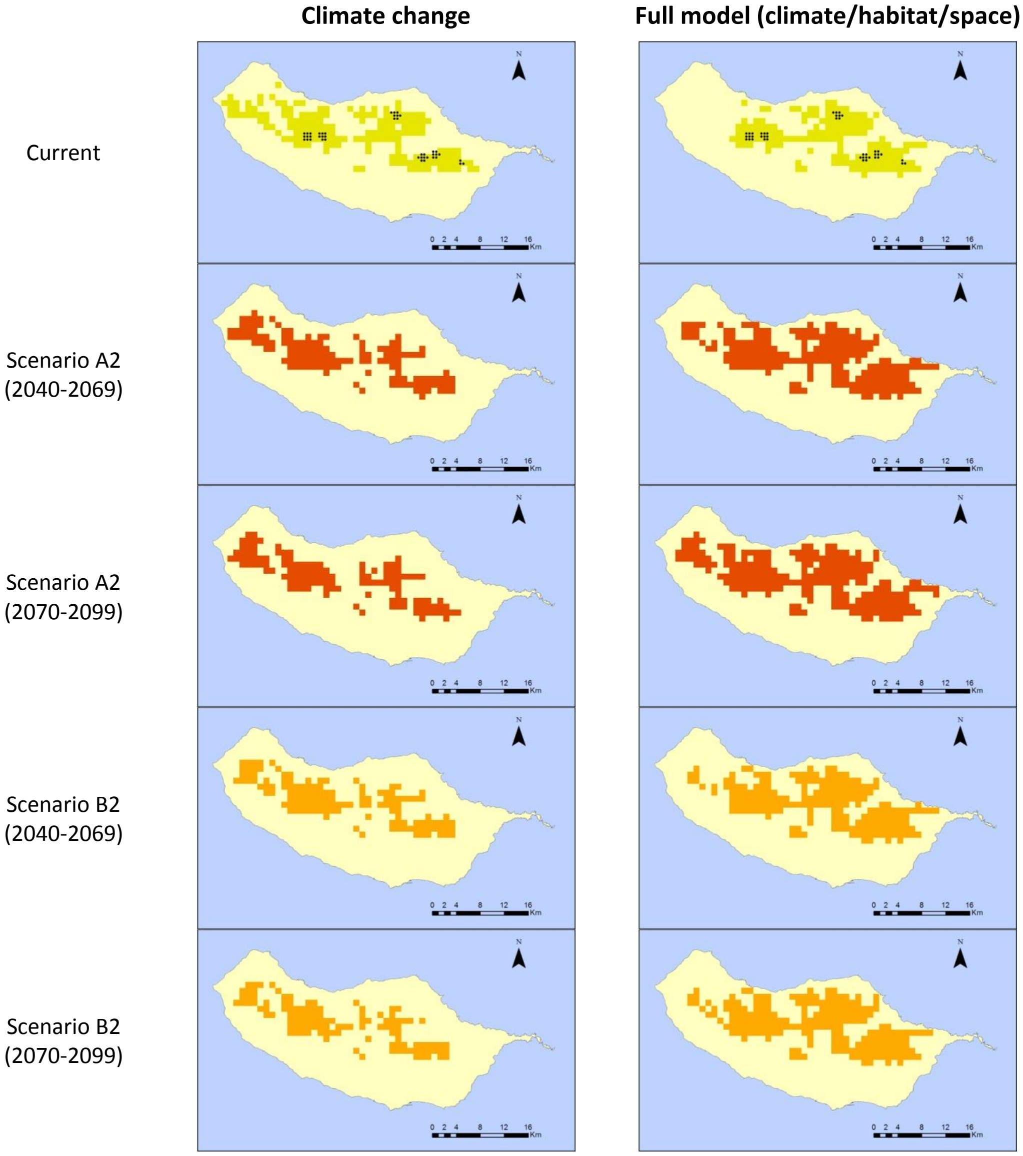

Figure 13: Predictive distribution maps for *Lauria fanalensis*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

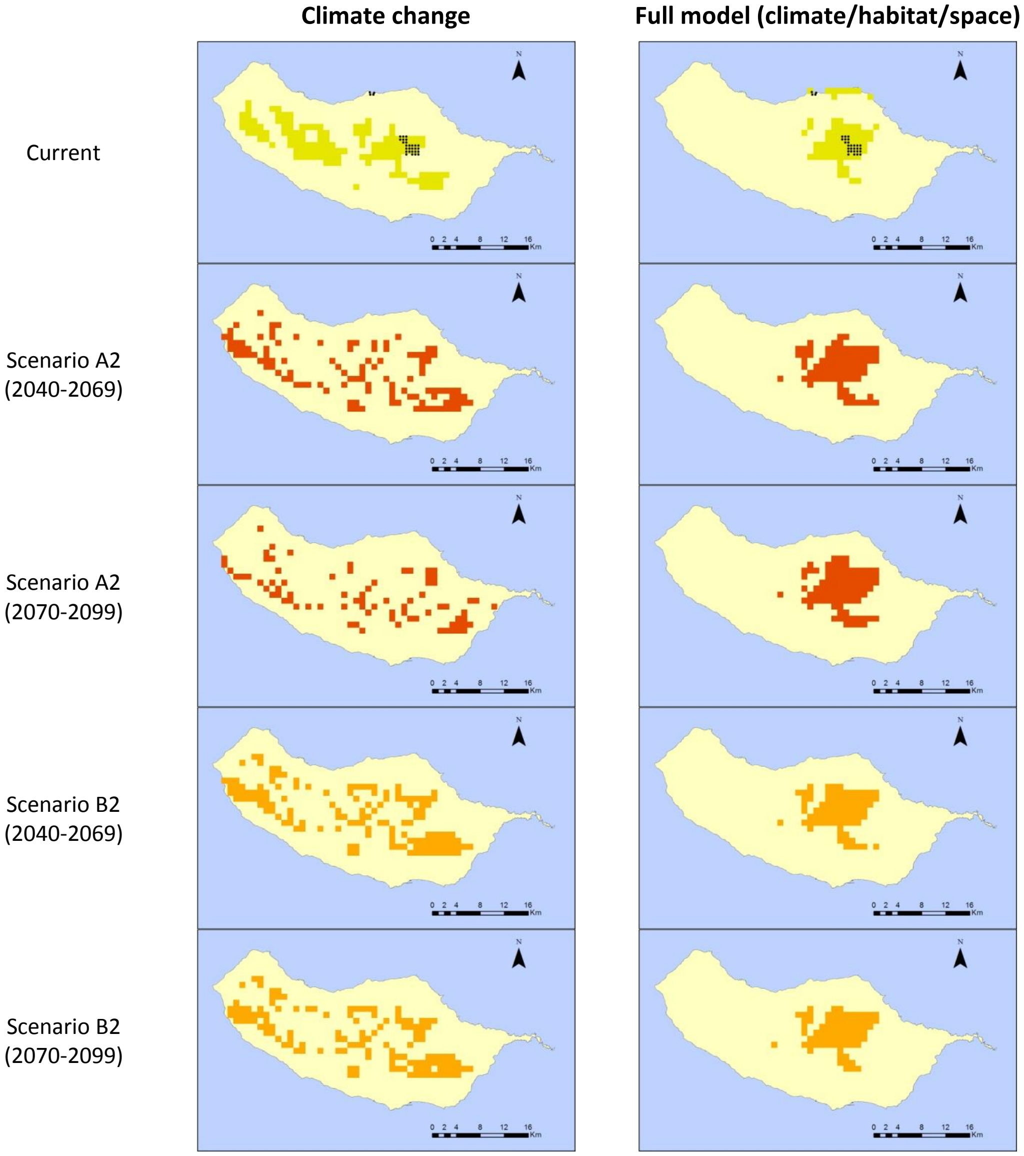

Figure 14: Predictive distribution maps for *Leiostyla arborea*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Leiostyla colvillei and *Leiostyla heterodon* are mainly found at high elevations, on the summit areas of the island. *L. colvillei* is one of the smallest species in Madeira and normally occurs in litter ledges within *Erica arborea* and Laurel trees. According to the climate model, potential distribution areas for *L. colvillei* can be found in the central and western part of the island at intermediate and high altitudes (Figure 15), and future projections suggest an increase of suitable areas for this species. For *L. heterodon* the scenario seems to be alarming (Figure 16); few potential areas were identified for this species and projections show that future suitable climate conditions might disappear.

As a result of its restriction to high elevations, both species' distribution is mainly influenced by the presence of native herbaceous areas, longitude and climate variables. Our full model suggests a considerable reduction on suitable habitat for *L. colvillei* (up to 90% in A2 scenario) and the possible extinction of *L. heterodon*, as a result of the decrease in suitable areas (100% in both scenarios).

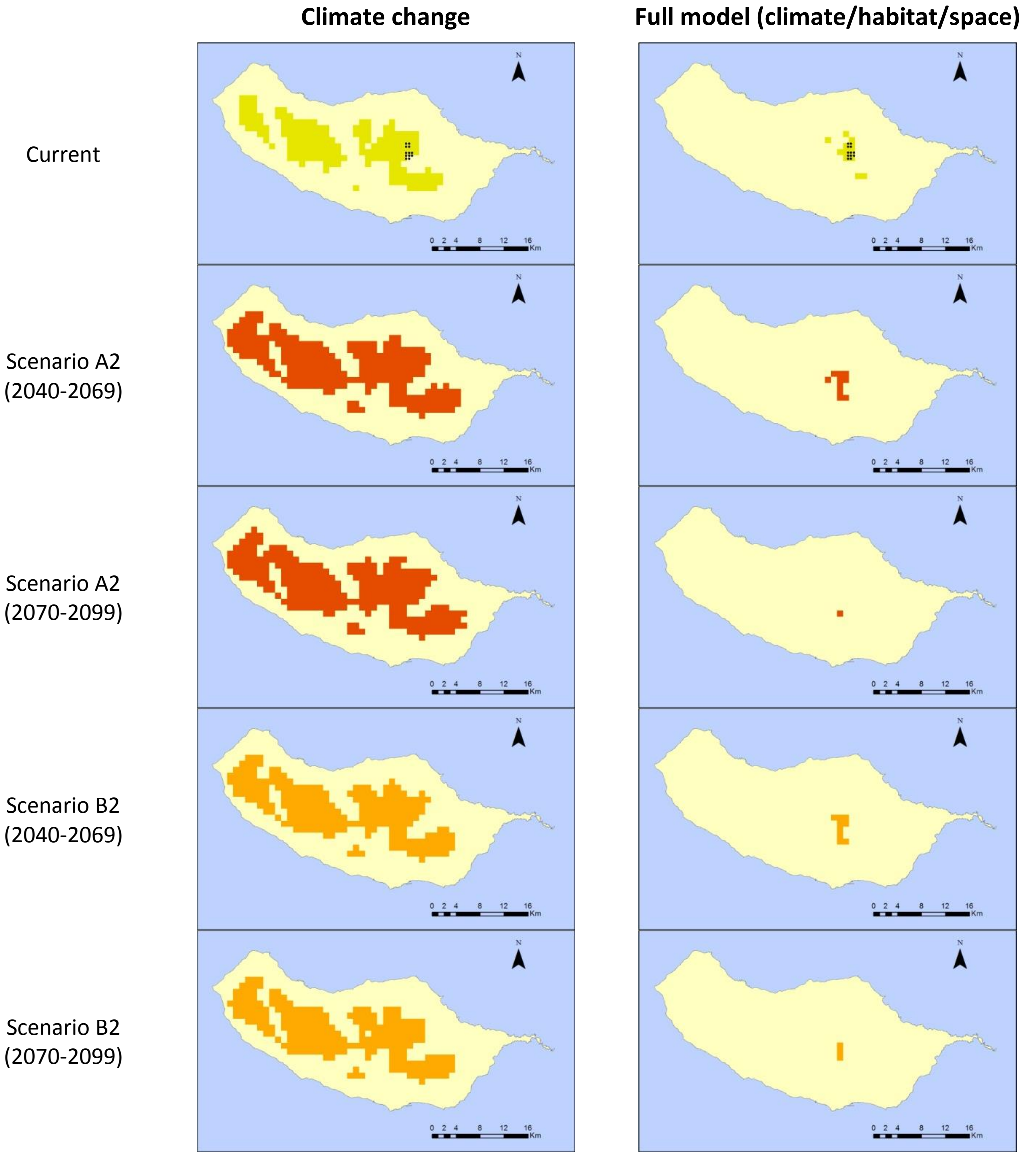

Figure 15: Predictive distribution maps for *Leiostyla colvillei*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

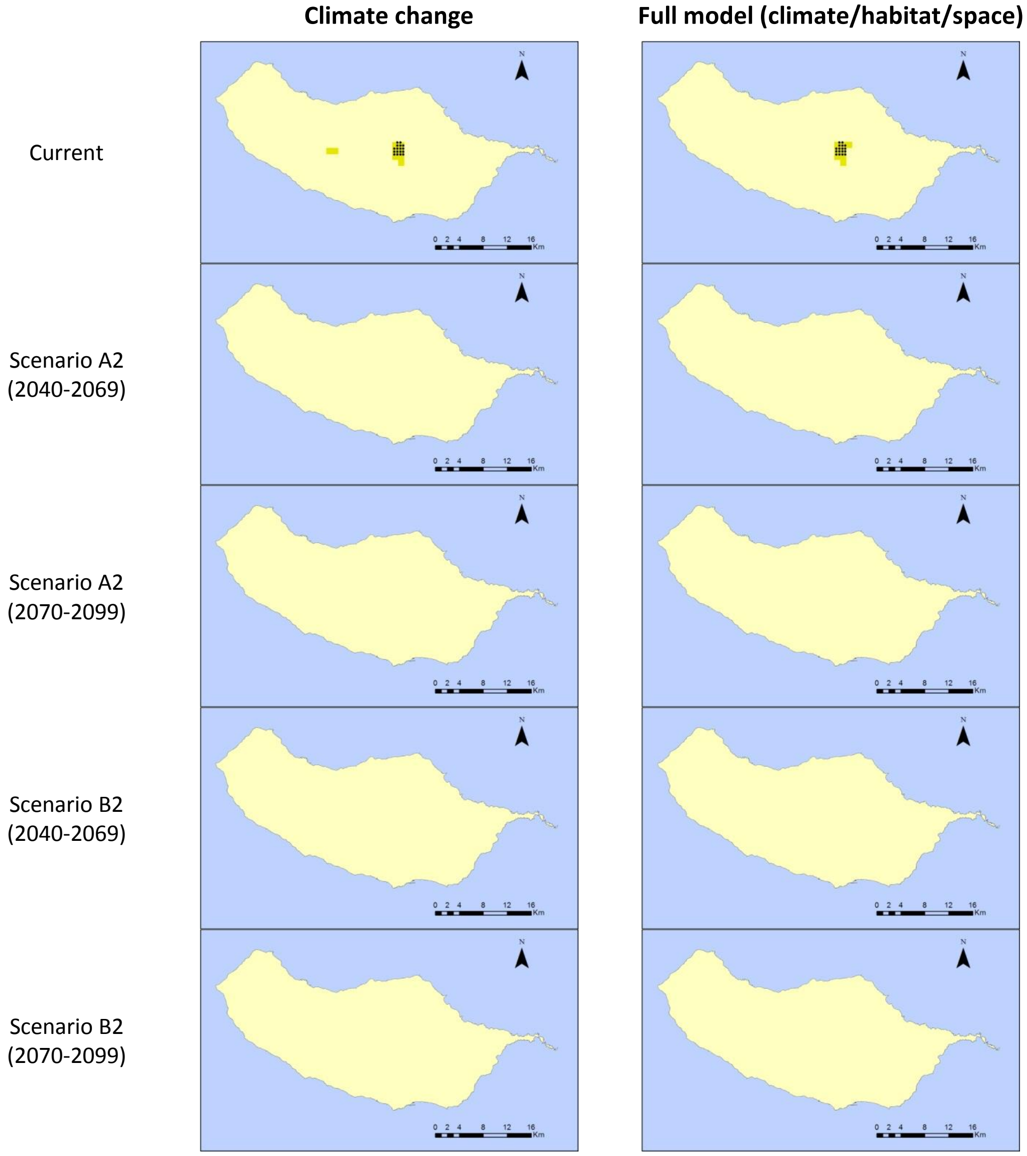

Figure 16: Predictive distribution maps for *Leiostyla heterodon*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Leiostyla concinna and *Leiostyla laurinea* are very rare and only known to occur in the central summit areas of the island, near Pico do Areeiro and Ribeira de Santa Luzia. *L. concinna* is normally associated with the soil, found amongst rock soil and leaf-litter on crags; and *L. laurinea* is arboreal, found on trunks of Laurel trees. With very restricted distributions, our model identified new potential sites for both species' survival. While *L. concinna* seems more confined to the east-central part of the island (Figure 17), *L. laurinea* (Figure 18) also occur in the western plateau of Paul da Serra.

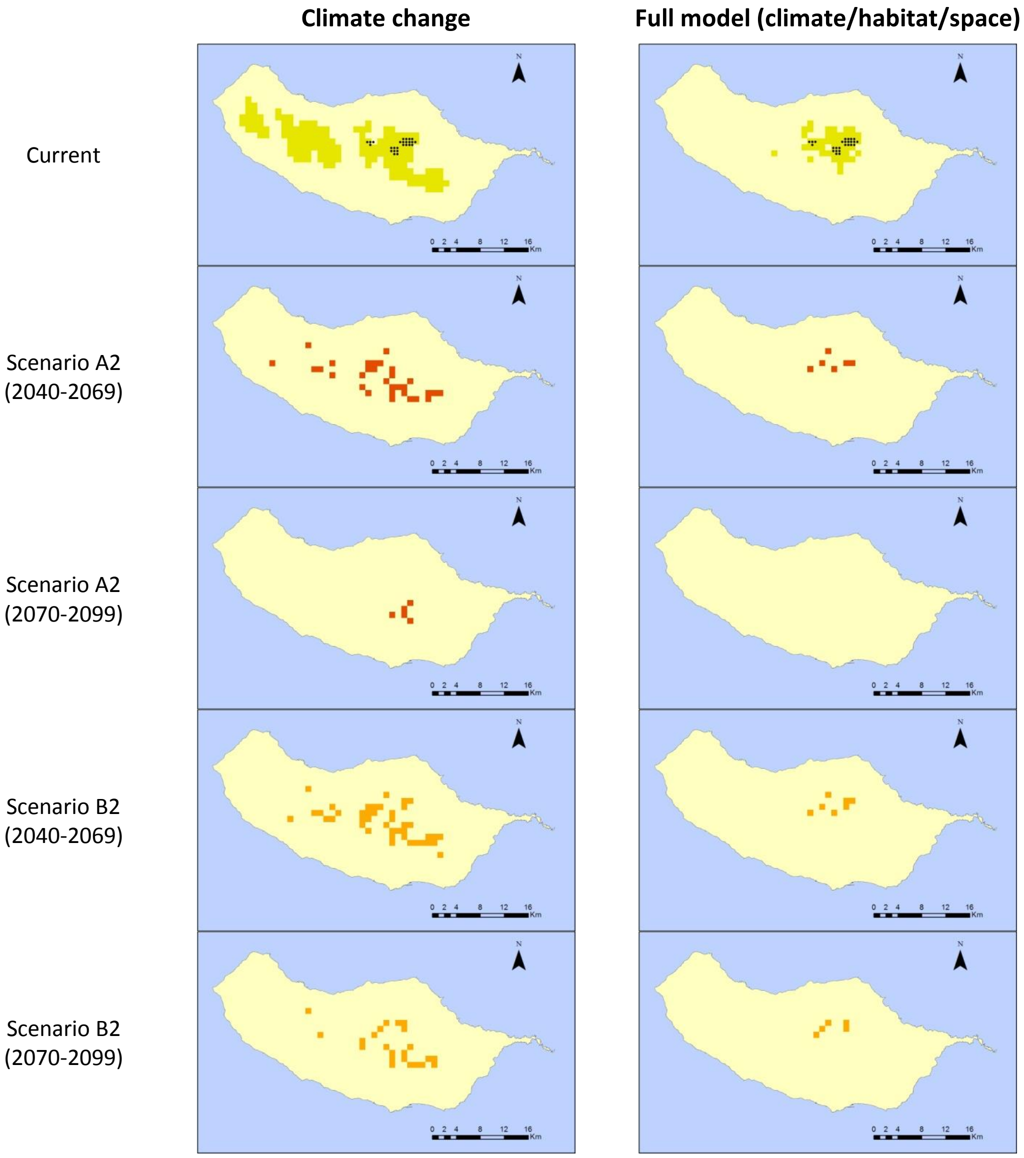

Figure 17: Predictive distribution maps for *Leiostyla concinna*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

According to future projections of climate only, suitable areas demonstrate a negative tendency, especially accentuated in the case of *L. concinna* (roughly less 95% of the current area, in A2 scenario). The presence of shrub areas, precipitation and longitude, in the case of *L. concinna,* and the presence of forested areas, longitude and latitude, in the case of *L. laurinea*, were the variables suggested by our full model to explain species distribution. New suitable areas were identified for both species, with a slight increase for *L. laurinea*. For *L. concinna*, the projected suitable area will suffer a pronounced decrease, between 80% and 100%, in A2 scenario.

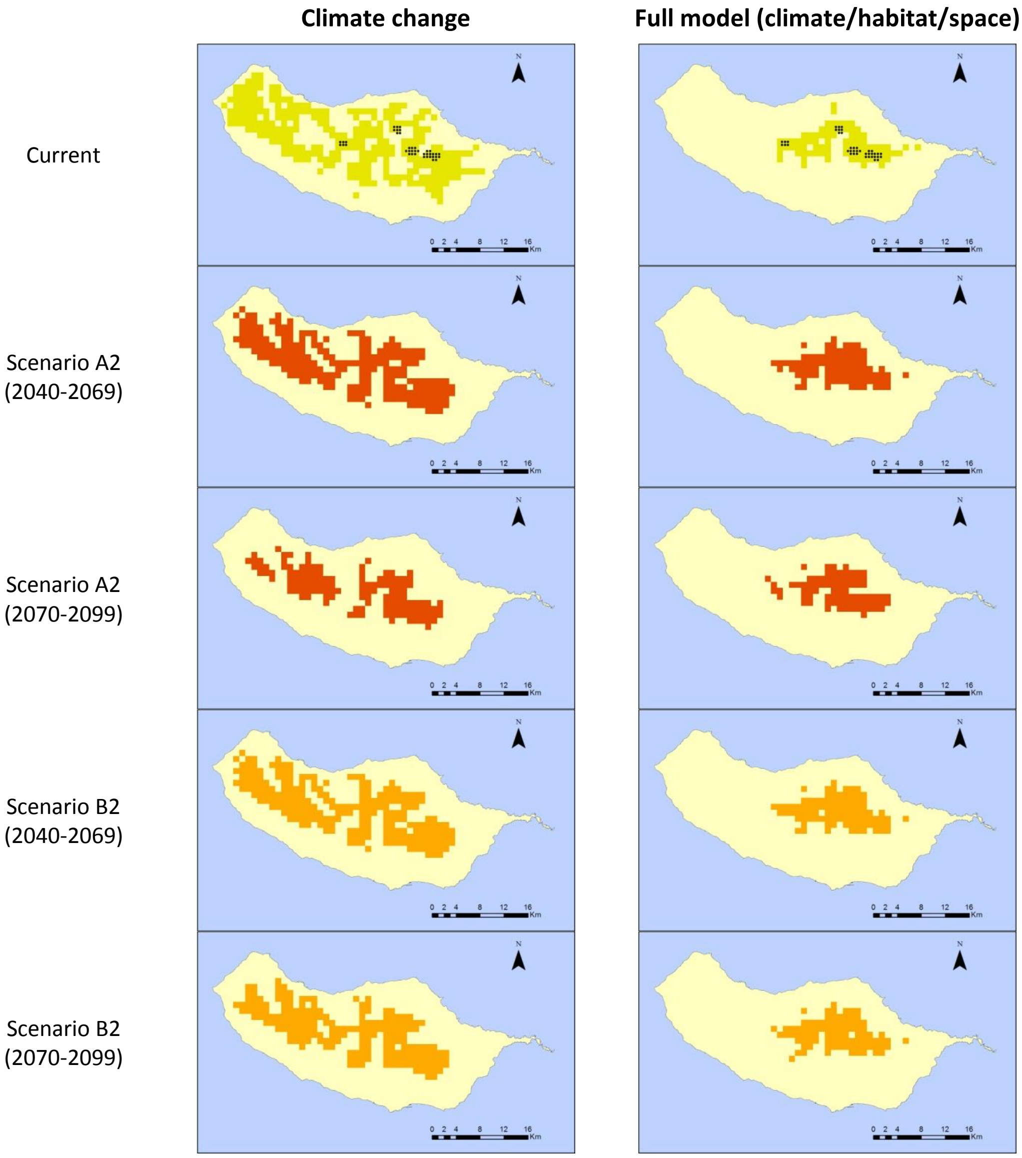

Figure 18: Predictive distribution maps for *Leiostyla laurinea*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Leiostyla cassida is mainly found at intermediate elevations and in the north coast. Both models identified new potential distribution areas mainly in the central and northern side of the island (Figure 19). Future projections under climate change indicate a reduction in suitable areas for *L. cassida*, up to 60% in A2 scenario. According to our full model, *L. cassida* is largely restricted by longitude and presence of herbaceous vegetation, and future projections suggest that suitable areas for species distribution will be reduced (by around 35%).

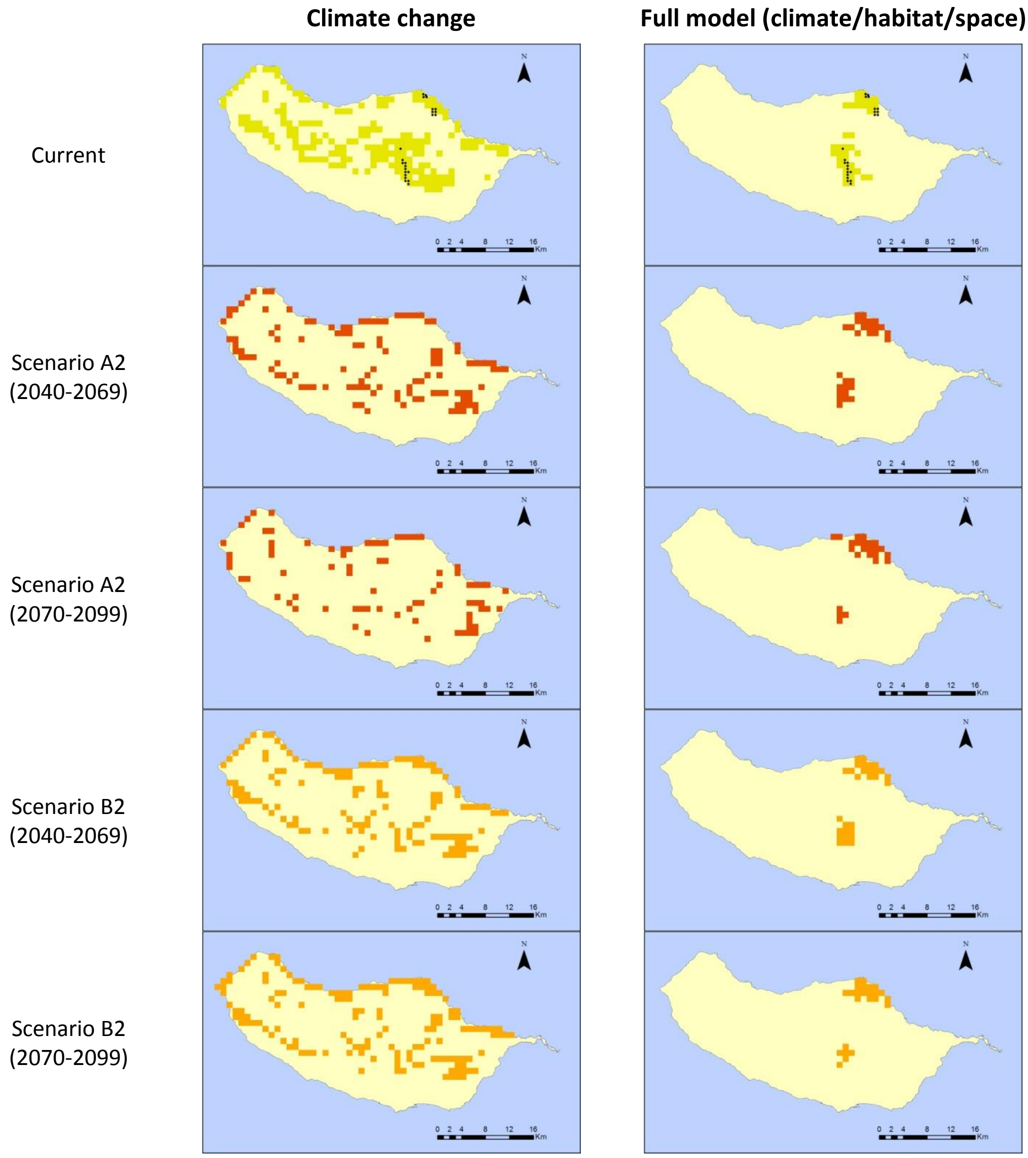

Figure 19: Predictive distribution maps for *Leiostyla cassida*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Mainly known to occur in the central areas of the island, near Pico do Areeiro and Ribeira de Santa Luzia, *Leiostyla falknerorum* is found in grass tufts and leaf-litter close to rock crags. New potential distribution areas were found around known areas and in the western part of the island (Figure 20). Future climate scenarios project a drastic decrease in suitable areas, for both scenarios (60 to 100%). According to our full model, *L. falknerorum* distribution is influenced by latitude, presence of forested areas, precipitation and humidity. Although suitable areas were found, future scenarios show a general negative trend.

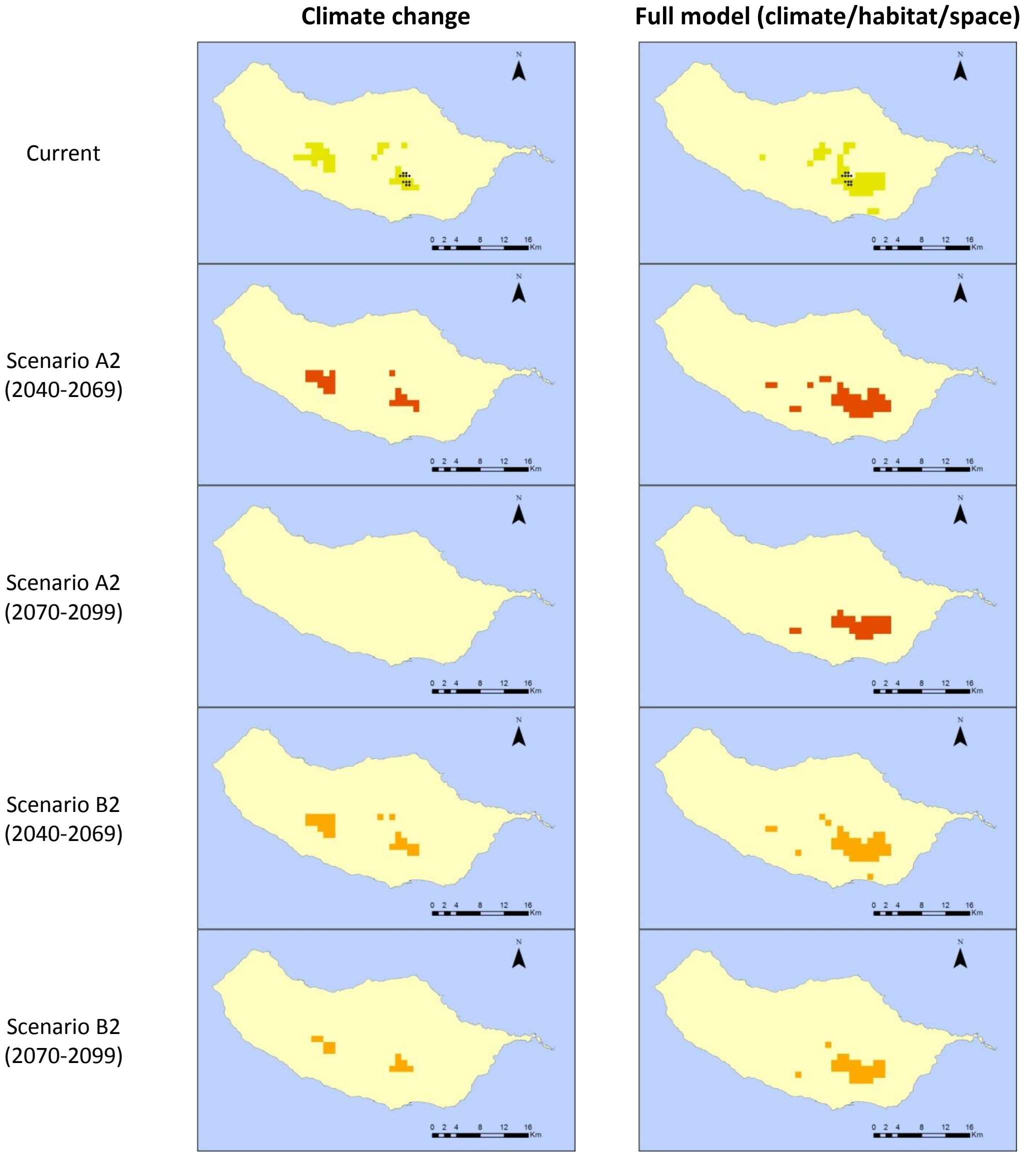

Figure 20: Predictive distribution maps for *Leiostyla falknerorum*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Leiostyla cheilogona and *Leiostyla loweana* are mainly distributed in the northern, central and western side of the island, at intermediate elevations. While *L. cheilogona* is normally found amongst leaf-litter and on ferns, *L. loweana* is often associated with *Marchantia* on rock crags and near waterfalls. According to the climate model, new distribution sites were suggested for both species. Future projections indicate a decrease in suitable areas for *L. cheilogona* (up to 20%; Figure 21), while *L. loweana* (Figure 22) shows some slighter decrease (around 10%). According to the full model, both species range are highly influenced by longitude, latitude and presence of forested areas. While *L.*

cheilogona's suitable areas are likely to decrease (up to 25%), *L. loweana* shows no clear trend on future projections.

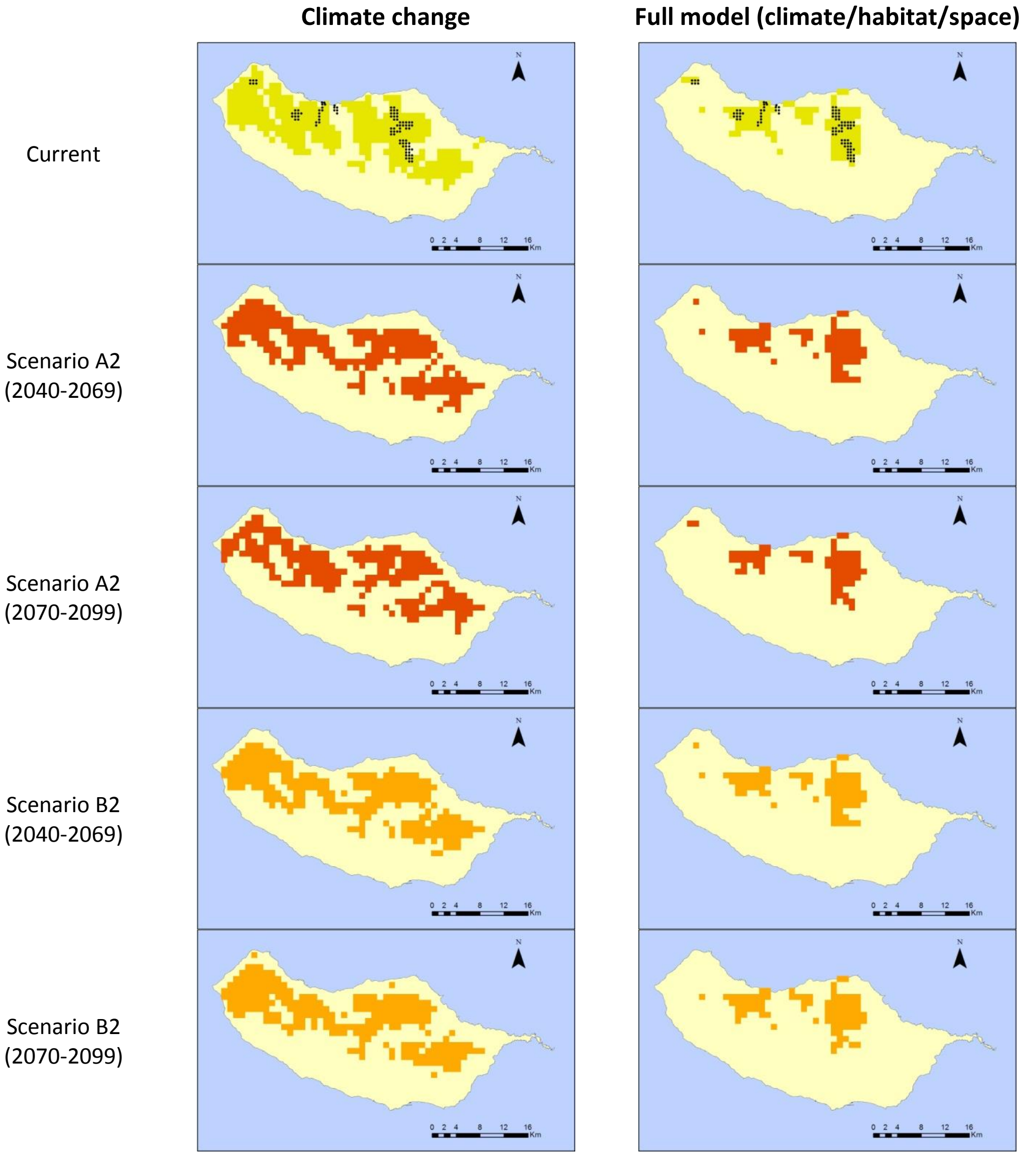

Figure 21: Predictive distribution maps for *Leiostyla cheilogona*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

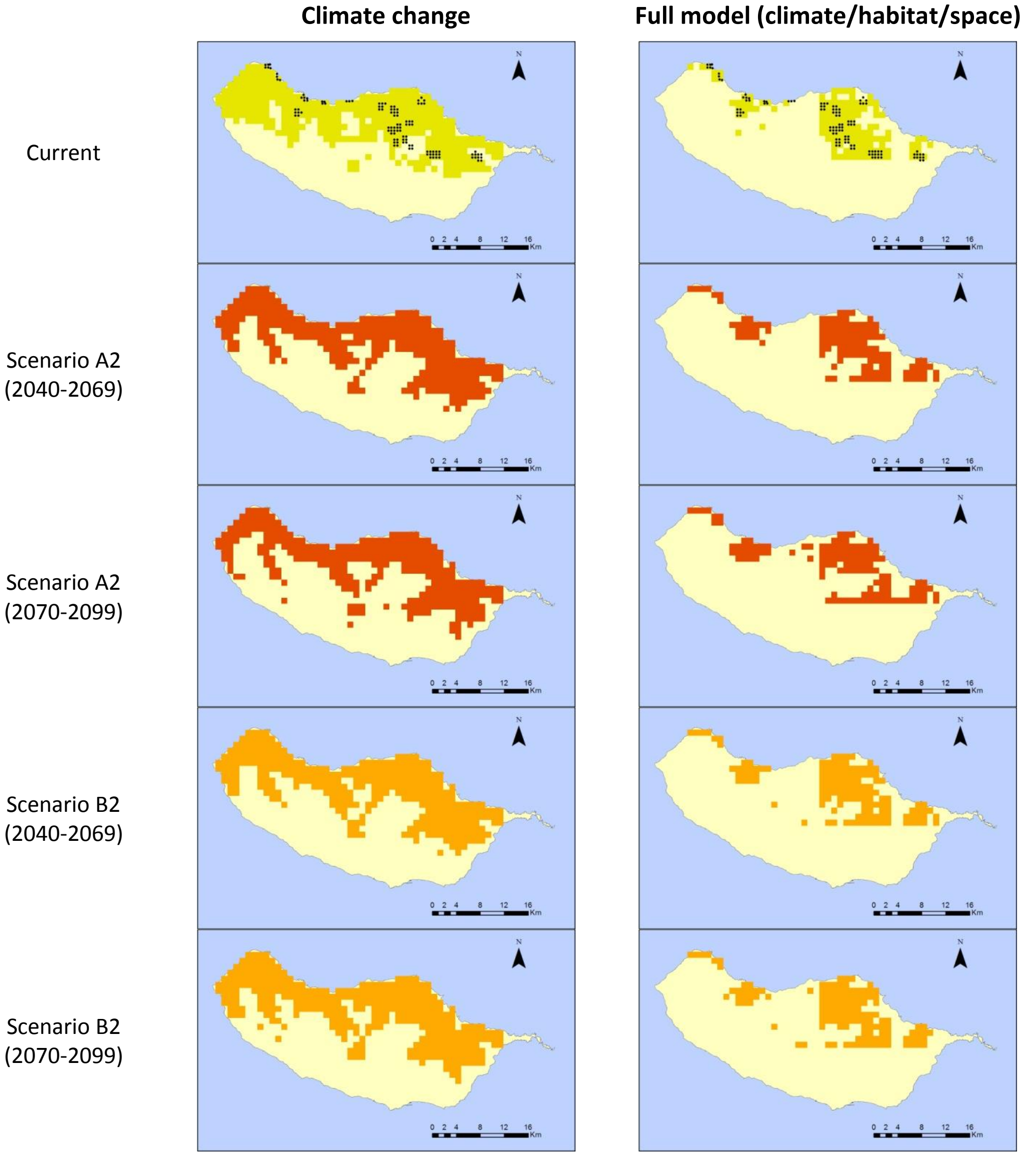

Figure 22: Predictive distribution maps for *Leiostyla loweana*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Leiostyla irrigua occurs in central Laurel forest and north coast, at intermediate elevations. It is humidity dependent, normally being found on wet rock surfaces, associated with *Marchantia* and dripping grasses, near waterfalls. New potential distribution sites were identified in the surrounding of known distribution areas and also in the south side of the island (Figure 23). Projections under climate change scenarios, point to a reduction in suitable areas (up to 100% in A2 scenario). In addition to longitude, my full model suggested the presence of forested areas, precipitation and humidity are the key variables in species distribution. Although new potential distribution sites were identified in the surrounding of the known distribution, future projections indicate an accentuated reduction of suitable areas for the species (up to 77% in A2 scenario).

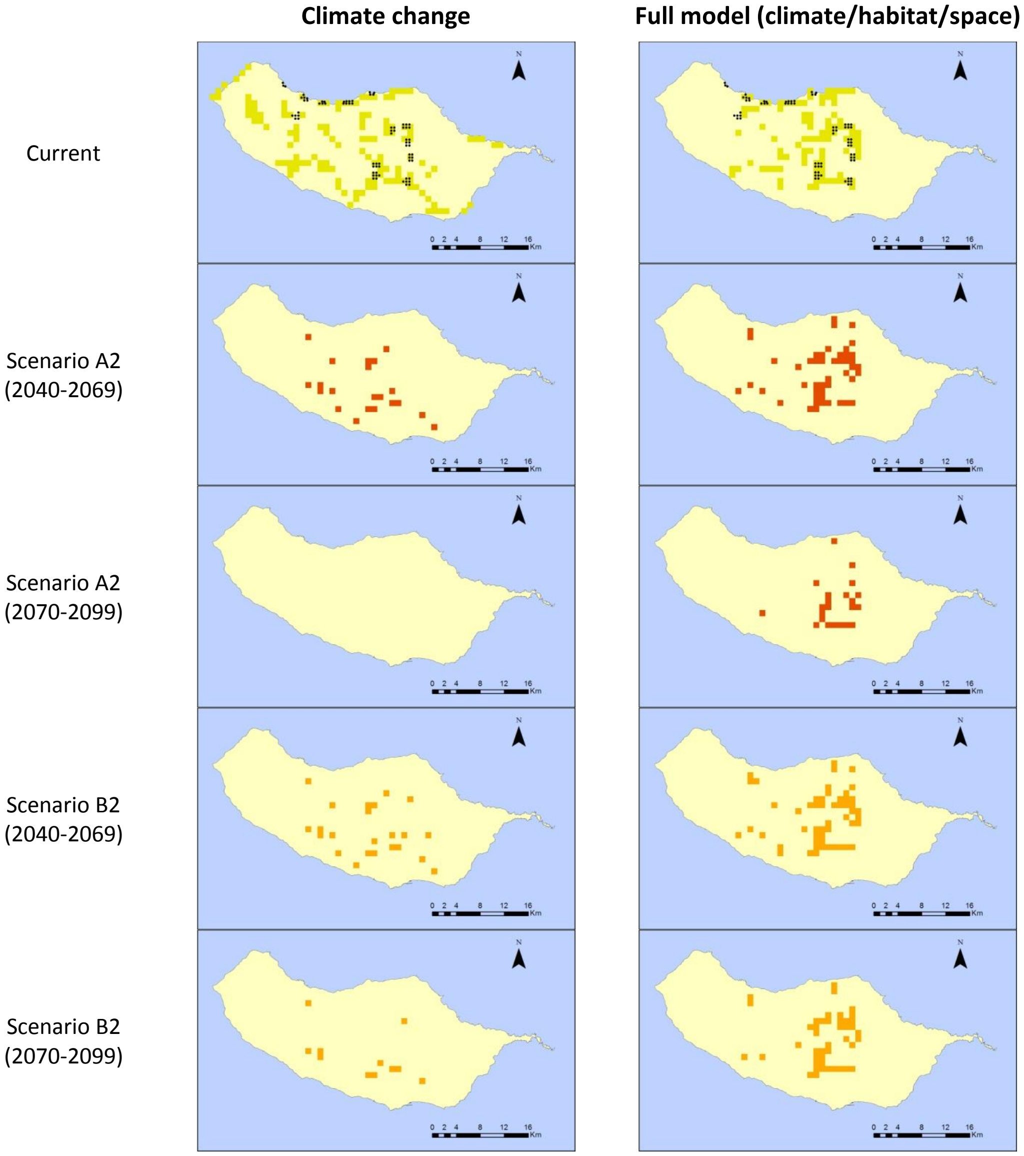

Figure 23: Predictive distribution maps for *Leiostyla irrigua*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Widespread at intermediate elevations, *Leiostyla sphinctostoma* is usually found on crags, from shaded to unshaded habitats, in the southern and northern sides of the island. According to the model, suitable areas were identified around known areas, and in the west central part of the island (Figure 24). Both projections, under future climatic scenarios, suggest a minor reduction in suitable areas for the species (under 5%).

According to the full model, new distribution sites were also identified. Future projections, for both the climate and full models, suggest an expansion in suitable area, up to 55%, in A2 scenario.

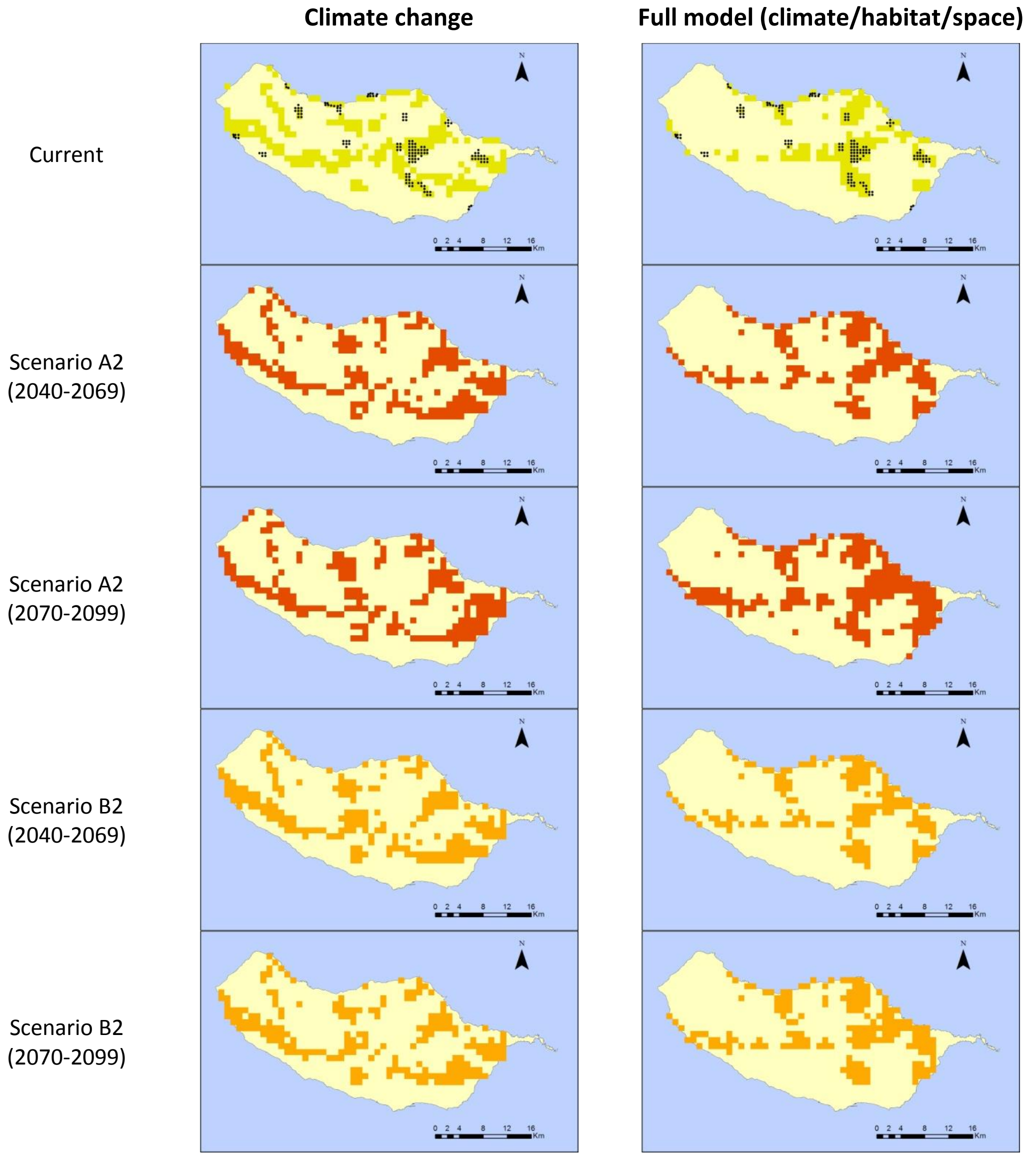

Figure 24: Predictive distribution maps for *Leiostyla sphinctostoma*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Leiostyla vincta vincta is normally found on *Marcanthia polymorpha* on the sea-cliffs. With a distribution limited to the north-west coast between São Vicente and Porto Moniz (Figure 25), current modelling predictions identify a wider suitable area, stretching from west to east, including Ponta de São Lourenço. Future climate scenarios suggest a negative trend for *L. vincta vincta* (around 20% for both scenarios). Our full model indicates that precipitation and latitude are the key variable in species distribution. Although current modelling predictions identify a wider distribution area, future scenarios suggests a reduction in suitable sites, with almost 15% less when compared to current modelled sites.

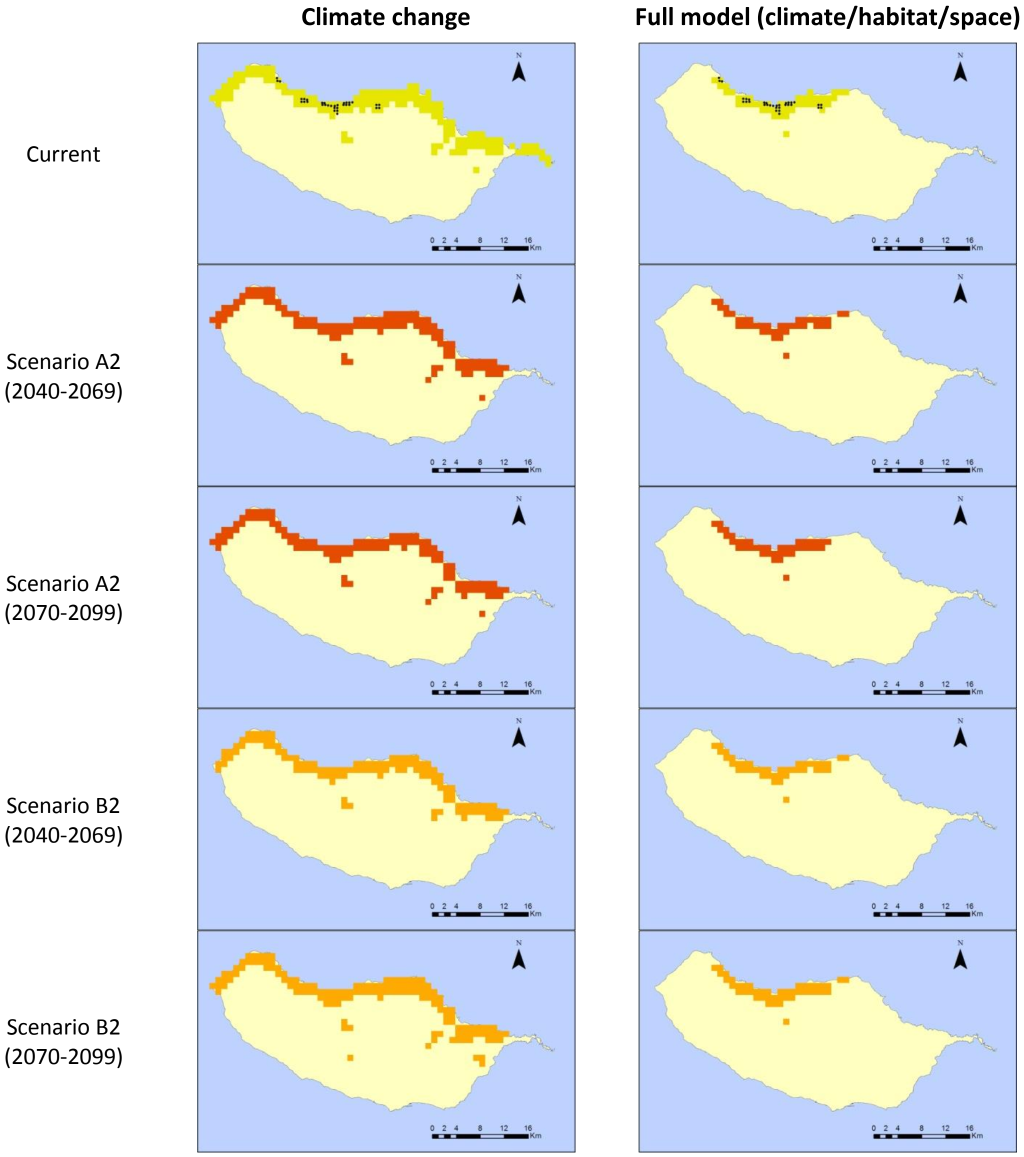

Figure 25: Predictive distribution maps for *Leiostyla vincta vincta*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Leiostyla vincta watsoniana is frequently associated to mosses and grasses on large rock crags and has a distribution limited to the north coast between São Vicente and Boaventura (Figure 26). The climate model identified a wider suitable area and future scenarios suggest an expansion of suitable sites (up to 50% in B2 scenario). Similarly to

L. vincta vincta, *L. vincta watsoniana* is highly influenced by precipitation and latitude; however the full model suggests a slight decrease in suitable sites for the species (up to 16% in A2 scenario).

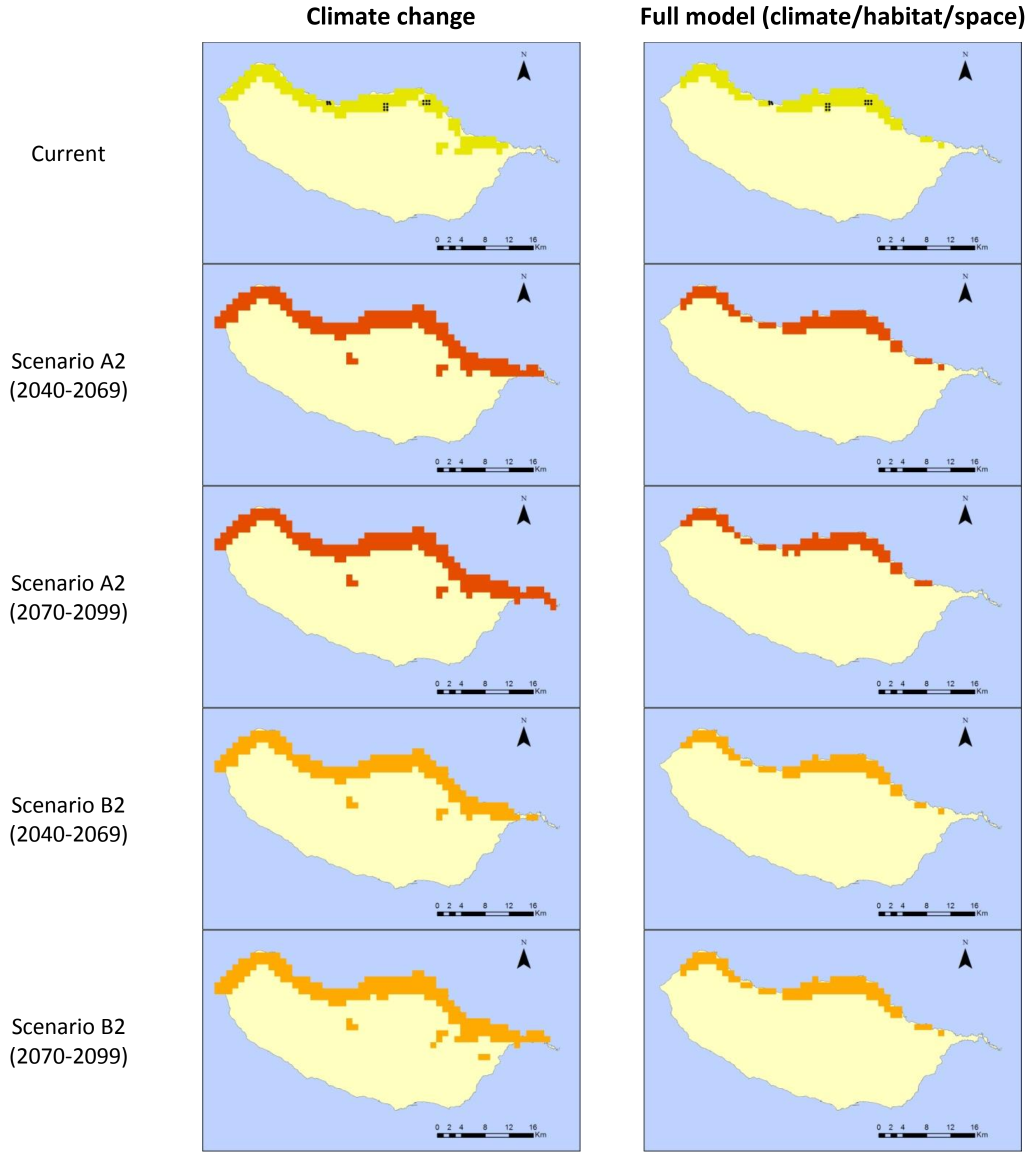

Figure 26: Predictive distribution maps for *Leiostyla vincta watsoniana*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

3.3.3. Clausiliidae

The Clausiliidae frequently includes climbing species, found on rock crags or in trees. The genus *Boettgeria* is endemic to the Madeiran archipelago. Listed by IUCN as of Least Concern, *Boettgeria crispa* is frequently found in the northern and central parts of the island, between 700 and 1000 meters high. Living mainly on tree trunks, it may also occur on dead wood and in the litter. According to the climate model, new areas were identified for potential distribution, around known areas and in the western part of the island, although the full model does not confirm this (Figure 27). Model predictions, under both scenarios, point to reduction of suitable sites, ranging from 46% in B2 and 80% in A2. In the full model, longitude, temperature and presence of forested areas are the driving variables of species distribution. With new potential distribution sites in the eastern and central part of the island, our model proposes a decrease in species future range (between 30% and 60%).

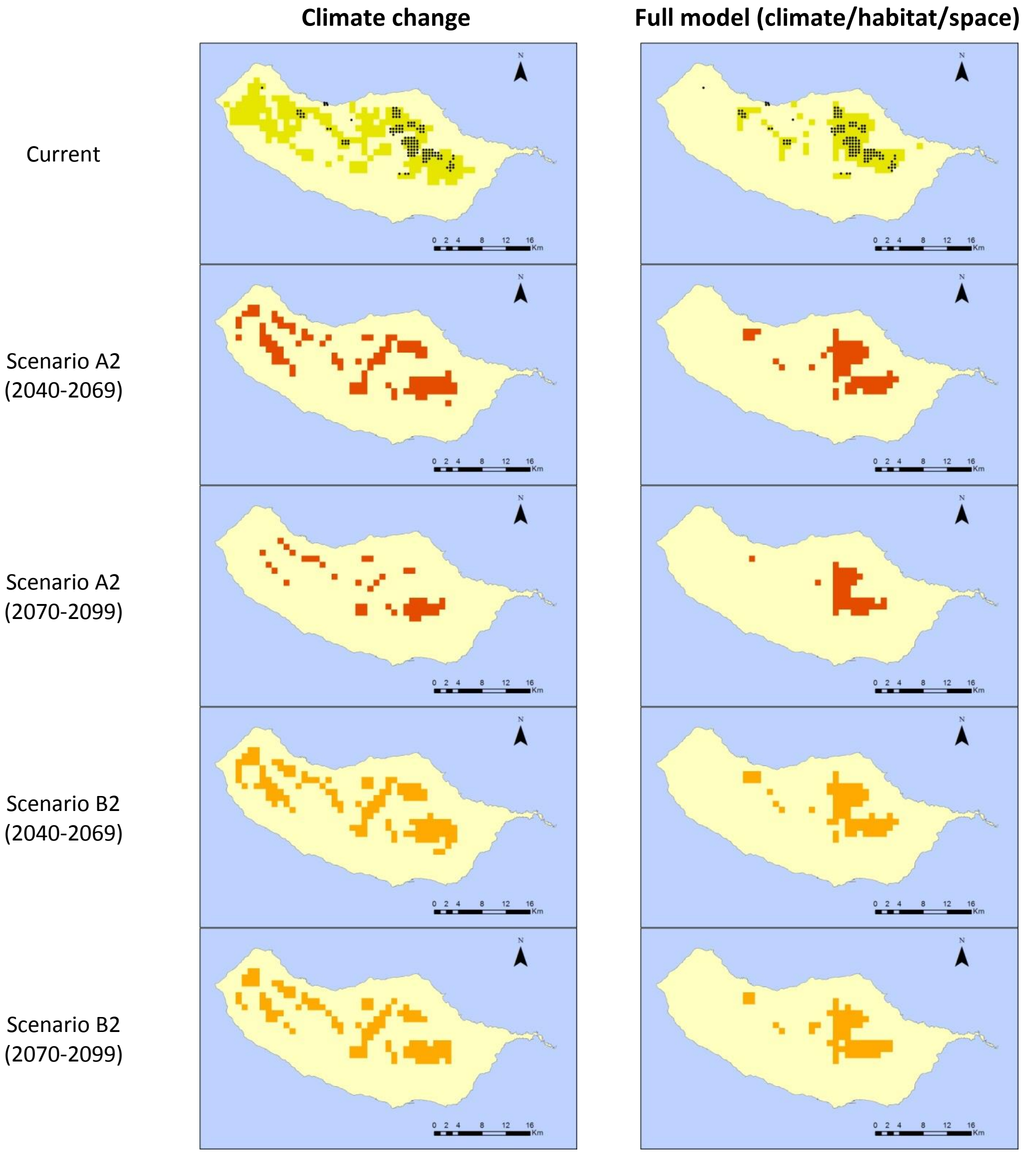

Figure 27: Predictive distribution maps for *Boettgeria crispa*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

3.3.4. Vitrinidae

This family is represented in Madeira by the genus *Plutonia*. As semi-slugs, all species are highly dependent on high humidity.

Plutonia albopalliata is the smallest semi-slug of the island and it is mainly found in the central areas, at intermediate and high elevations, and also near the north coast, were the Laurel forest extends nearly to the sea (Figure 28).

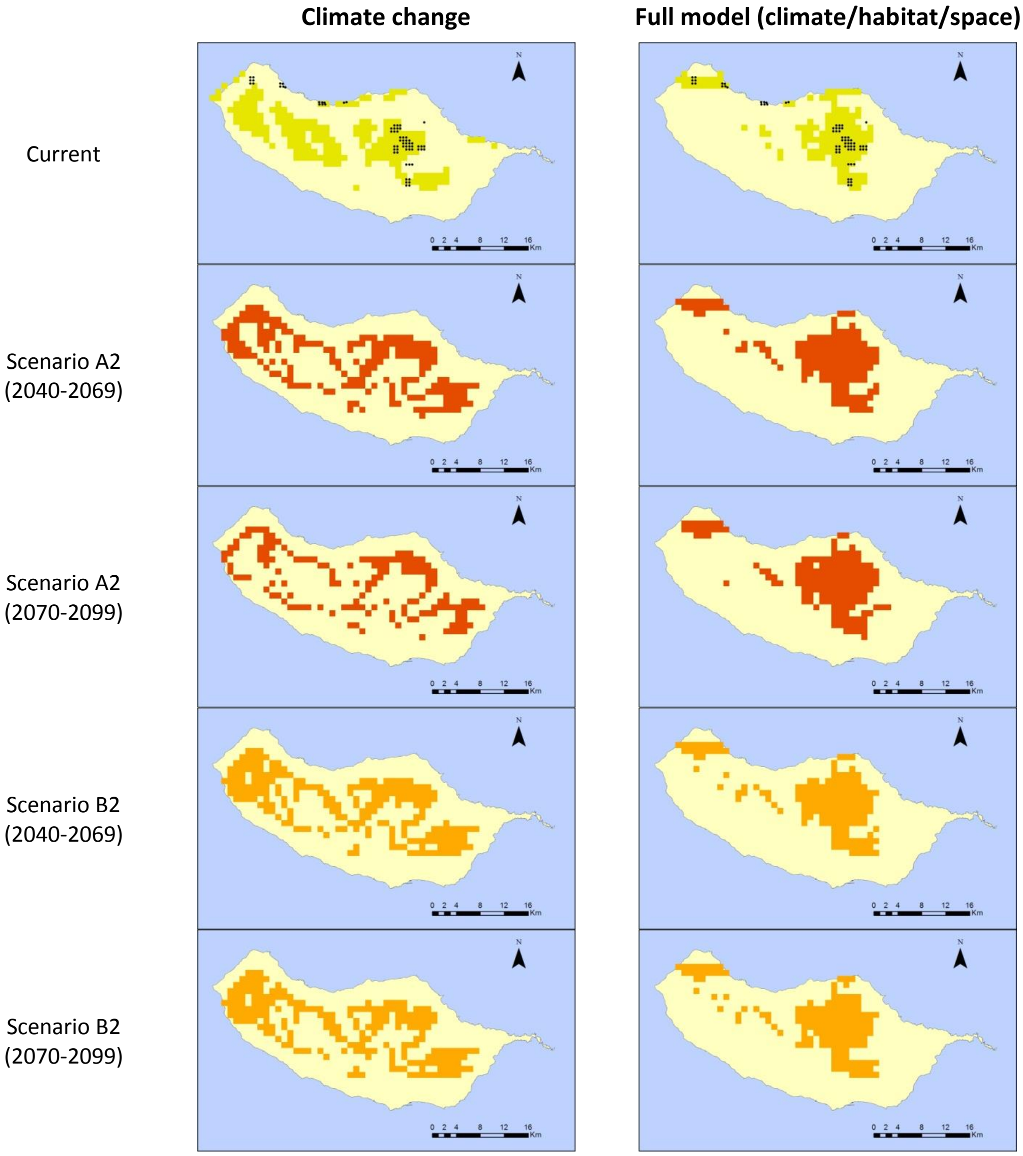

Figure 28: Predictive distribution maps for *Plutonia albopaliata*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Normally associated with wet habitats, this species can be found on vegetation and around rocky crags. Our climate model suggested the identification of new potential areas for *P. albopalliata*, especially in the western part of the island. Future projections suggest a reduction of suitable areas for species in the A2 scenario and a stable/slight positive trend in B2. For the full model, *P. albopalliata*'s distribution is highly dependent on longitude, precipitation and presence of forested areas. This model identified further potential areas for the presence *of P. albopalliata* and future projections indicate an increase in suitable area for the species (around 20% for both scenarios).

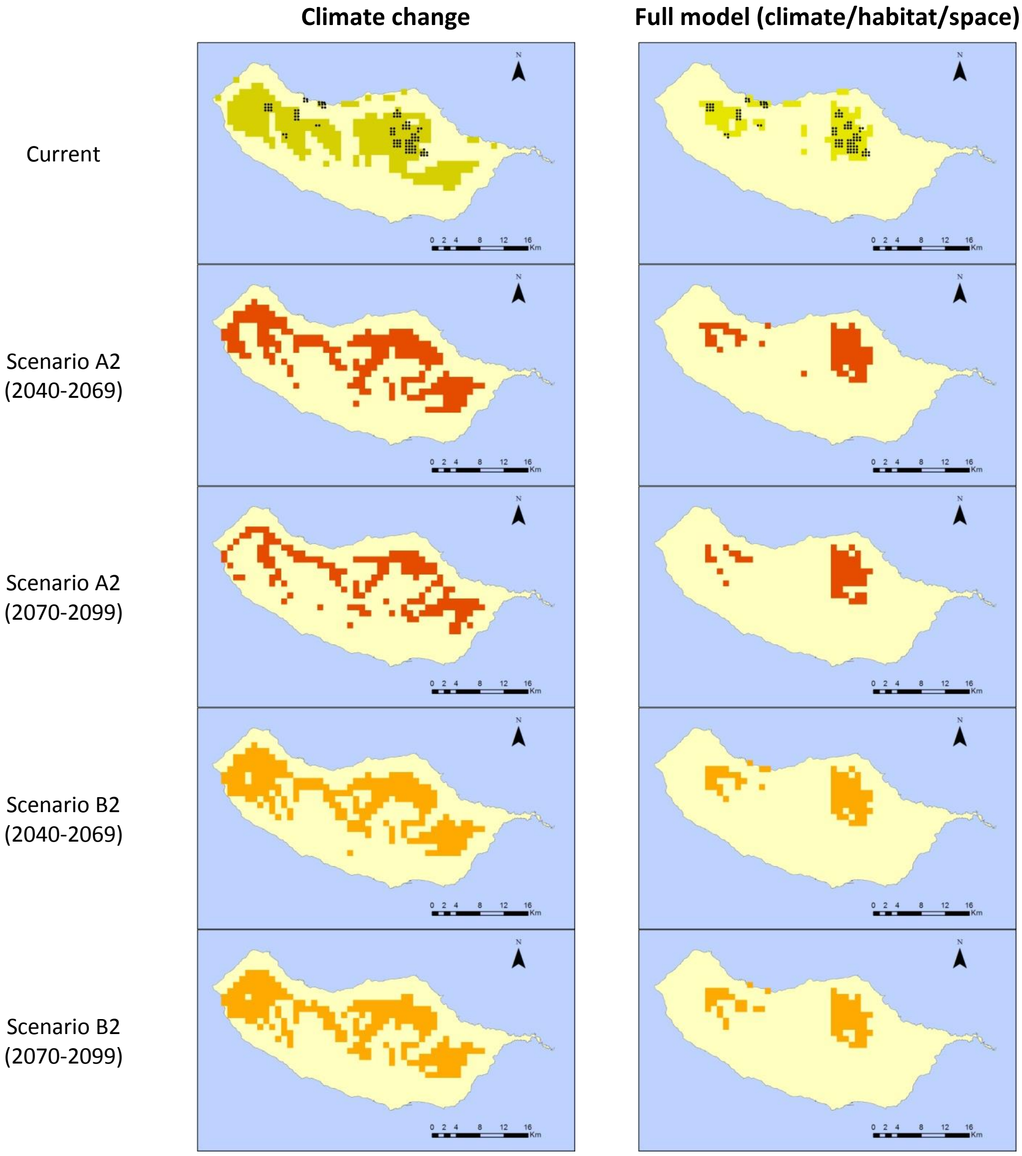

Figure 29: Predictive distribution maps for *Plutonia behnii*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Similarly to *P. albopalliata*, *Plutonia behnii* is restricted to the central and north part of the island. Its habitat requirements are Laurel forest at intermediate elevations. Current predictions suggest new distribution areas for *P. behnii* (Figure 29) and future climate models point to a reduction in species range, especially near the coastline. Our full model identified the presence of natural forest and longitude as the major variables contributing to species distribution and suggests a negative tendency in future scenarios (from 25%, in B2, to 40% in A2).

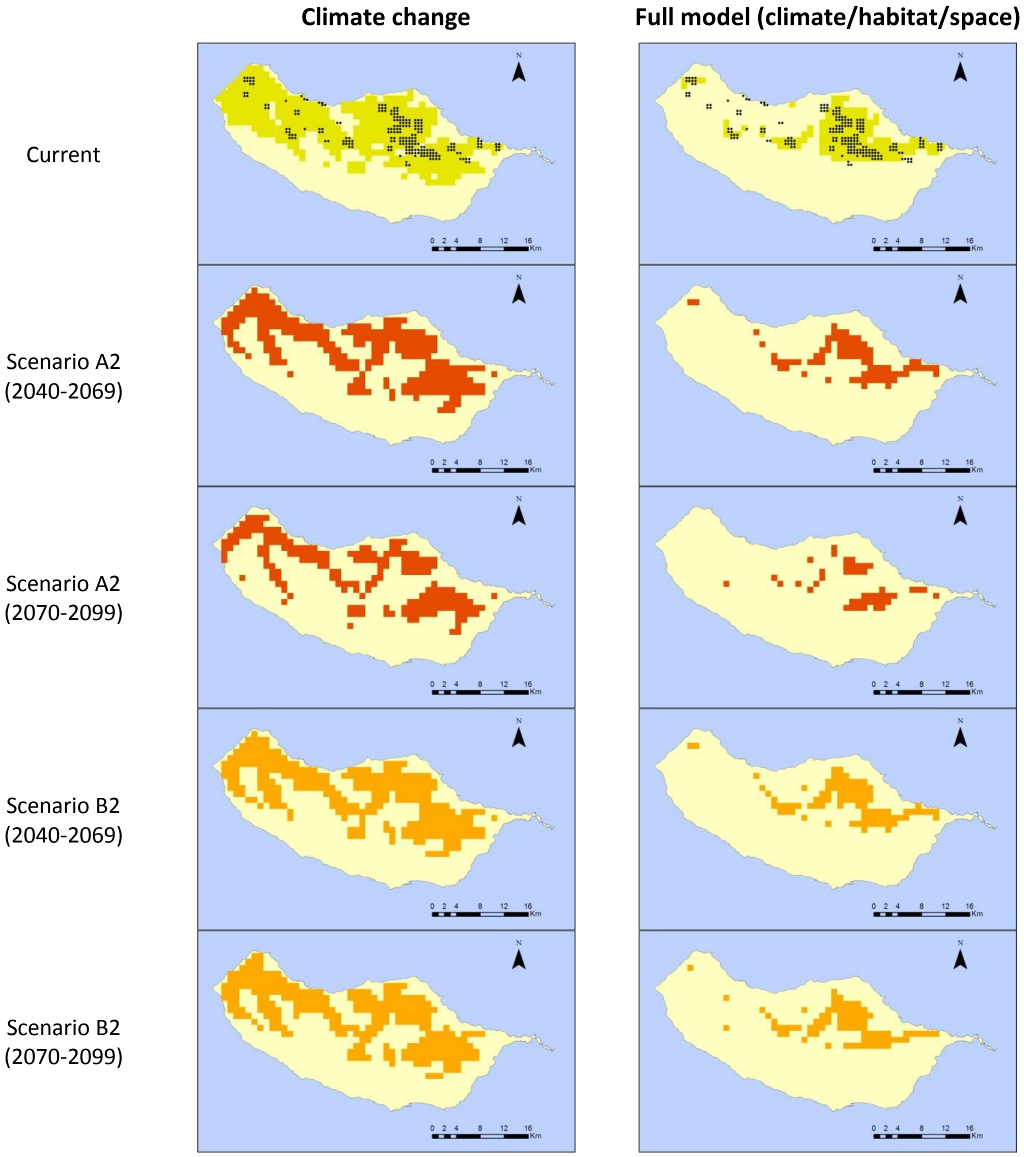

Figure 30: Predictive distribution maps for *Plutonia marcida*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

The larger *Plutonia* species, *P. marcida* (Figure 30), *P. nitida* (Figure 31) and *P. ruivensis* (Figure 32), are mainly found at intermediate elevations in the central/north side of the island, amongst leaf-litter, on leafs and trunks of Laurel trees and shaded crags, in areas of big humidity. Our model identified potential distribution areas for these species, concentrated around known occurrence sites. According to our climate model, due to climate change and high humidity dependency, all three species will experience a variable reduction in their distribution ranges, in all scenarios (between 25%, in A2, and 45% to 60%, in B2). The full model indicates that these species are mainly influenced by geographical variables and climate (especially temperature and precipitation), and, as a result, all three species will experience a negative trend in their distribution range (*P. marcida* might decrease its suitable area up to 67%).

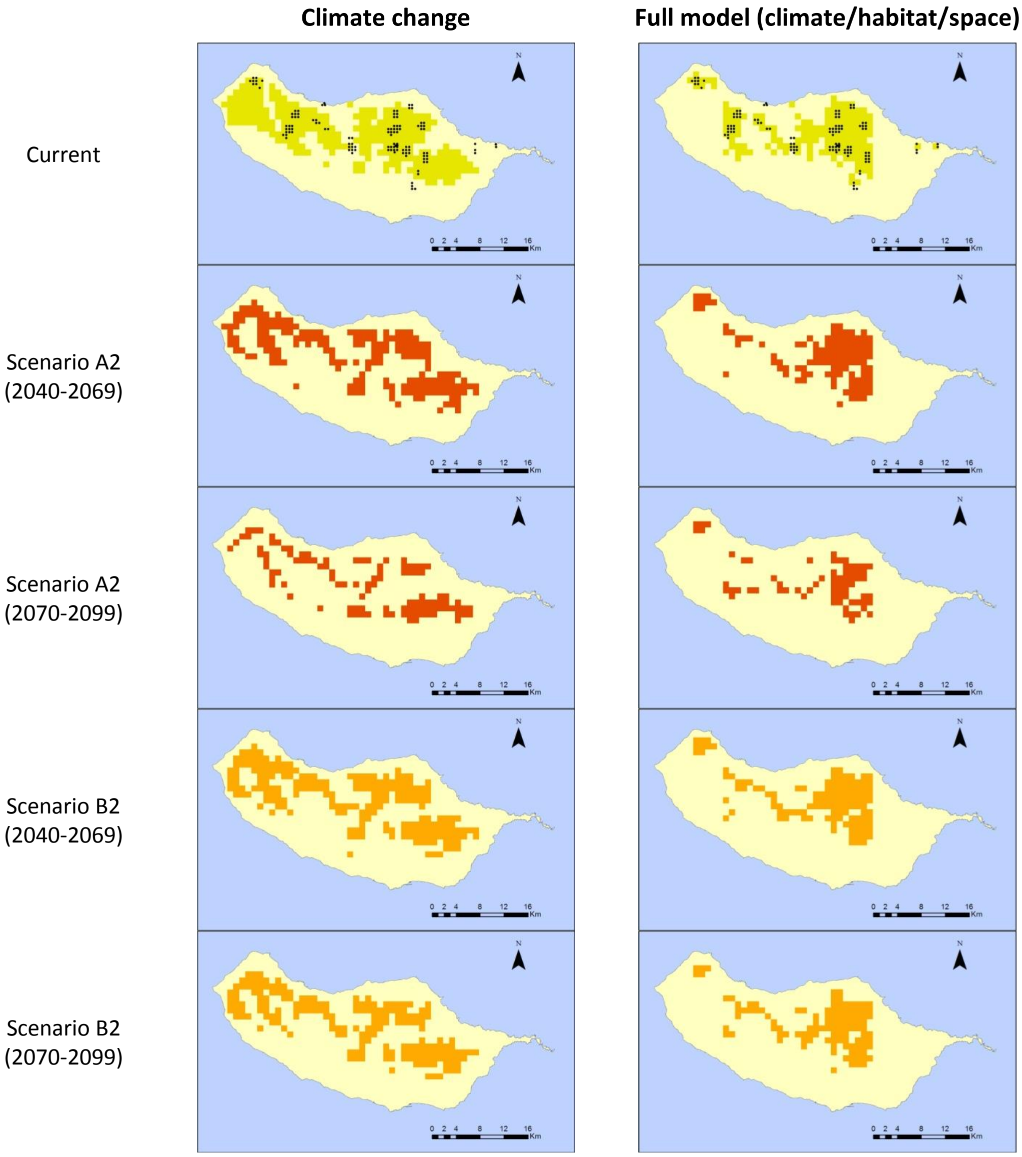

Figure 31: Predictive distribution maps for *Plutonia nitida*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

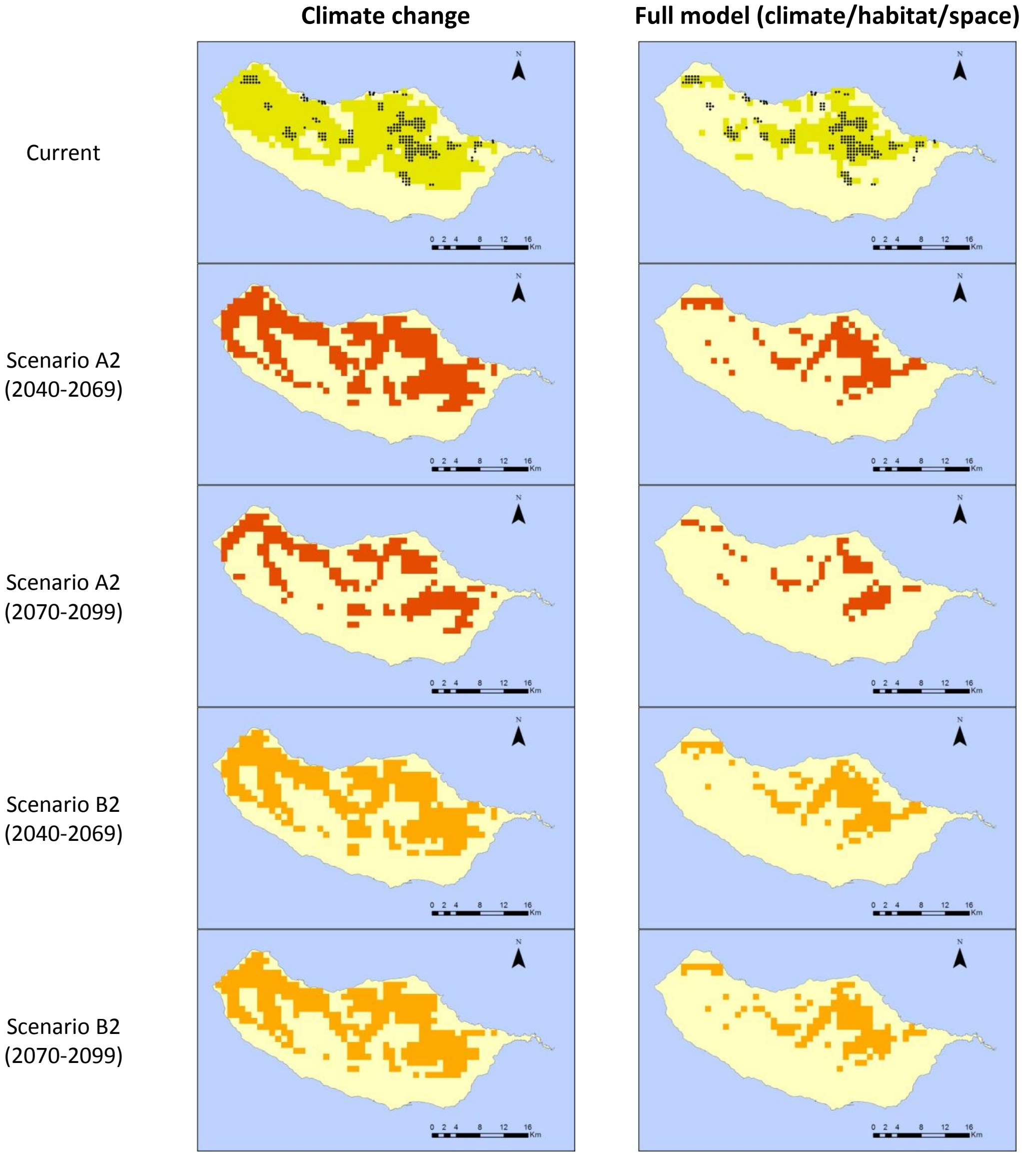

Figure 32: Predictive distribution maps for *Plutonia ruivensis*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

3.3.5. Hygromiidae

The Hygromiidae contain a very diverse set of species, with many different shell forms and habitat requirements. Within Laurel forest, 2 of *Geomitra*, 5 species of *Actinella*, 2 of *Leptaxis* and 1 of *Caseolus* are listed by IUCN.

Endemic to Madeira Island, *Geomitra tiarella* is normally found on coastal cliffs and steep slabs, amongst turfed grasses and herbs. According to the climate model, new presently suitable areas were identified for this species along the north coast of the island (Figure 33). Future projections suggest a decreasing tendency in area, for both scenarios (up to 100% in A2 scenario). The full model indicates that *G. tiarella* is mainly influenced by precipitation and latitude. Although new current potential distribution areas were identified, our model suggests that this species might face a considerable reduction in future suitable area (up to 70% in A2 scenario).

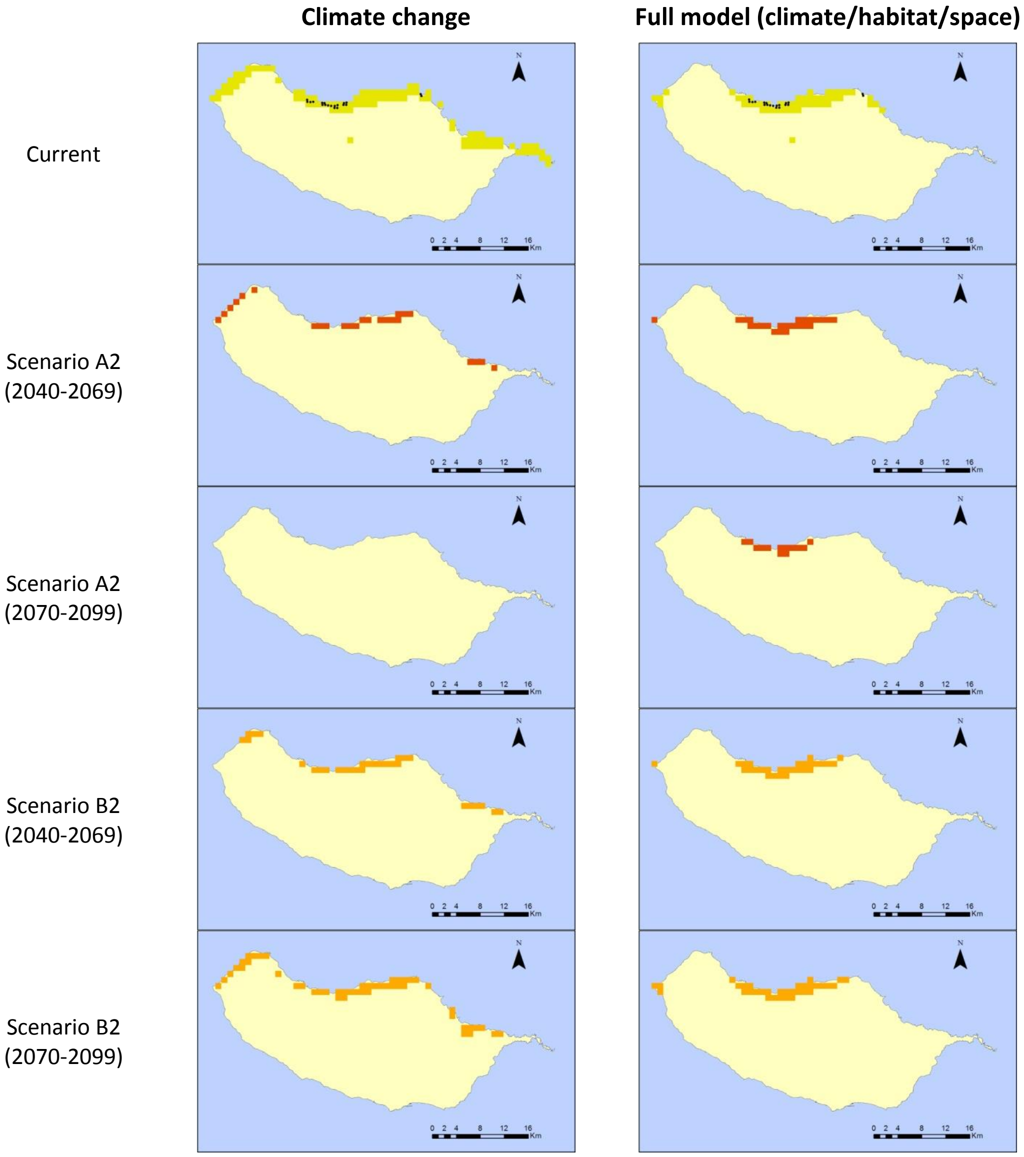

Figure 33: Predictive distribution maps for *Geomitra tiarella*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

On Madeira, *Actinella actinophora* is found in moist damp ravines and in leaf-litter at intermediate altitudes in the central part of the island. Near the north coast, where Laurel forest reaches the sea, it can be found on rock ledges of cliffs (Figure 34). Our climate model suggests new potential distribution areas, with adequate climatic conditions for *A.*

actinophora survival; however future predictions indicate a negative trend in suitable areas (up to 50%). *Actinella actinophora*'s distribution is mainly influenced by longitude, presence of forested areas and latitude, and although a wider distribution range was modelled to the current scenario, future habitat predictions state that species distribution may reduce (between 50% and 60%).

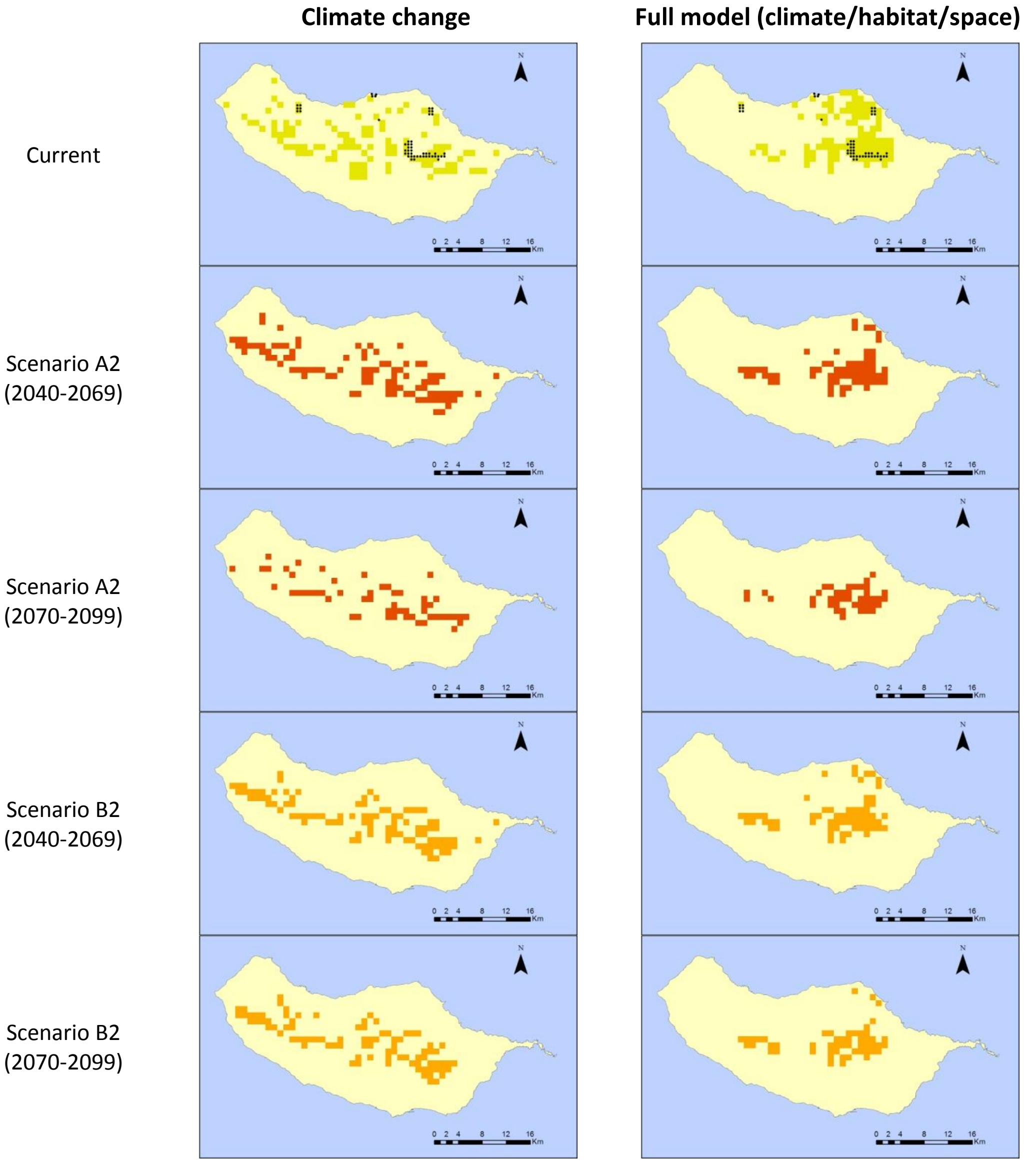

Figure 34: Predictive distribution maps for *Actinella actinophora*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Once described as common in the intermediate elevations north of Funchal (Wollaston, 1878), *Actinella arridens* is now rarely found (Figure 35). Our climate model suggests new potential distribution range and a future expansion on species suitable area. *A.*

arridens (influenced by longitude, relative humidity and precipitation) seems to expand their distribution under the full model, south towards.

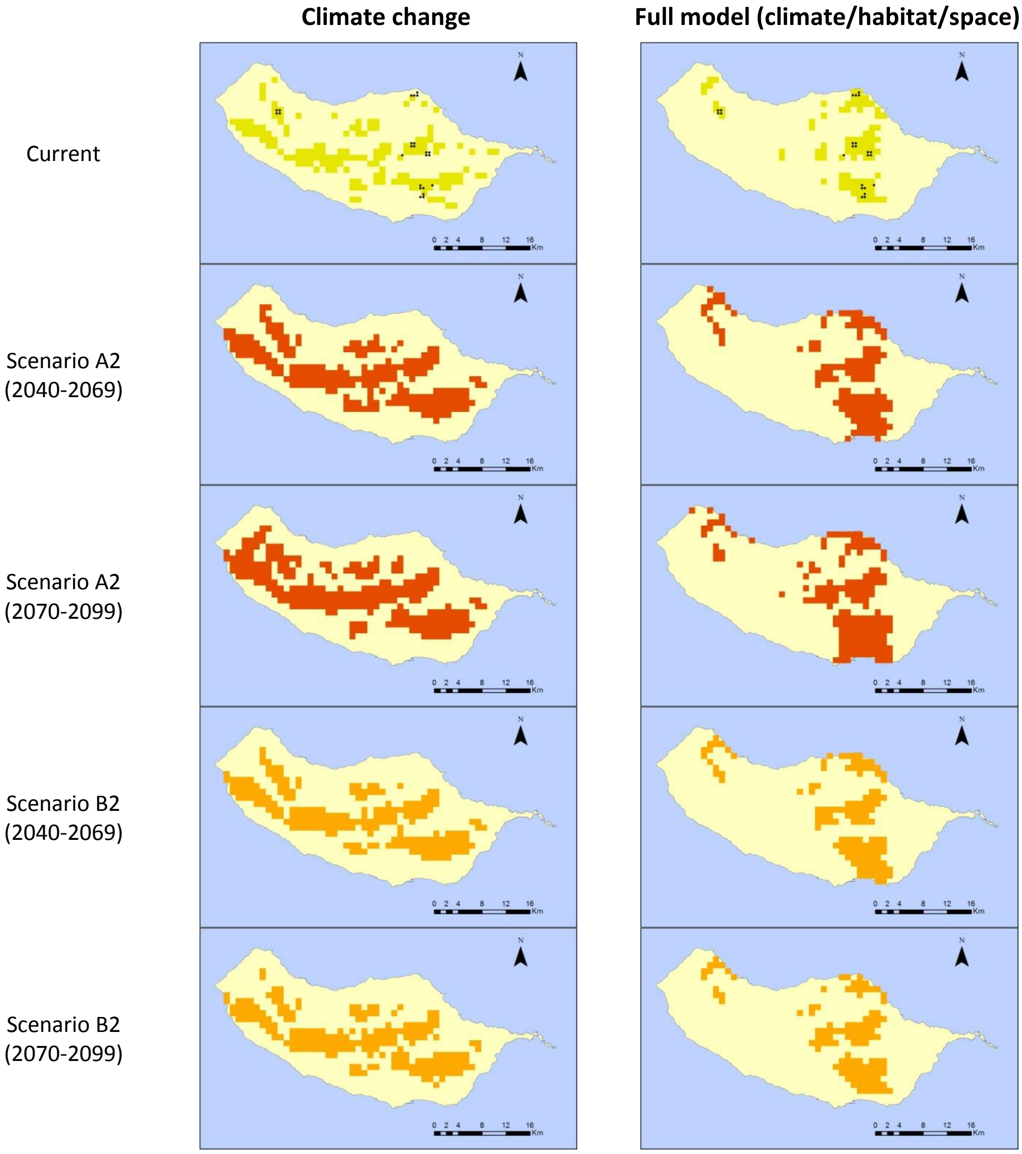

Figure 35: Predictive distribution maps for *Actinella arridens*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Mainly restricted to less disturbed habitats in the north of the island, *Actinella fausta* also occurs in the central southern side, associated to deep and humid cliffs. According to the model, new localities present suitable climate for *A. fausta* (Figure 36). The predicted suitable area for this species, in the future, will suffer a reduction from 30% to 45%. *A. fausta* is highly influenced by latitude, relative humidity and longitude, and according to the habitat model, new localities present suitable climate for *A. fausta* distribution, especially in the eastern part of the island. Future predictions suggest a negative tendency on suitable areas (up to 40%).

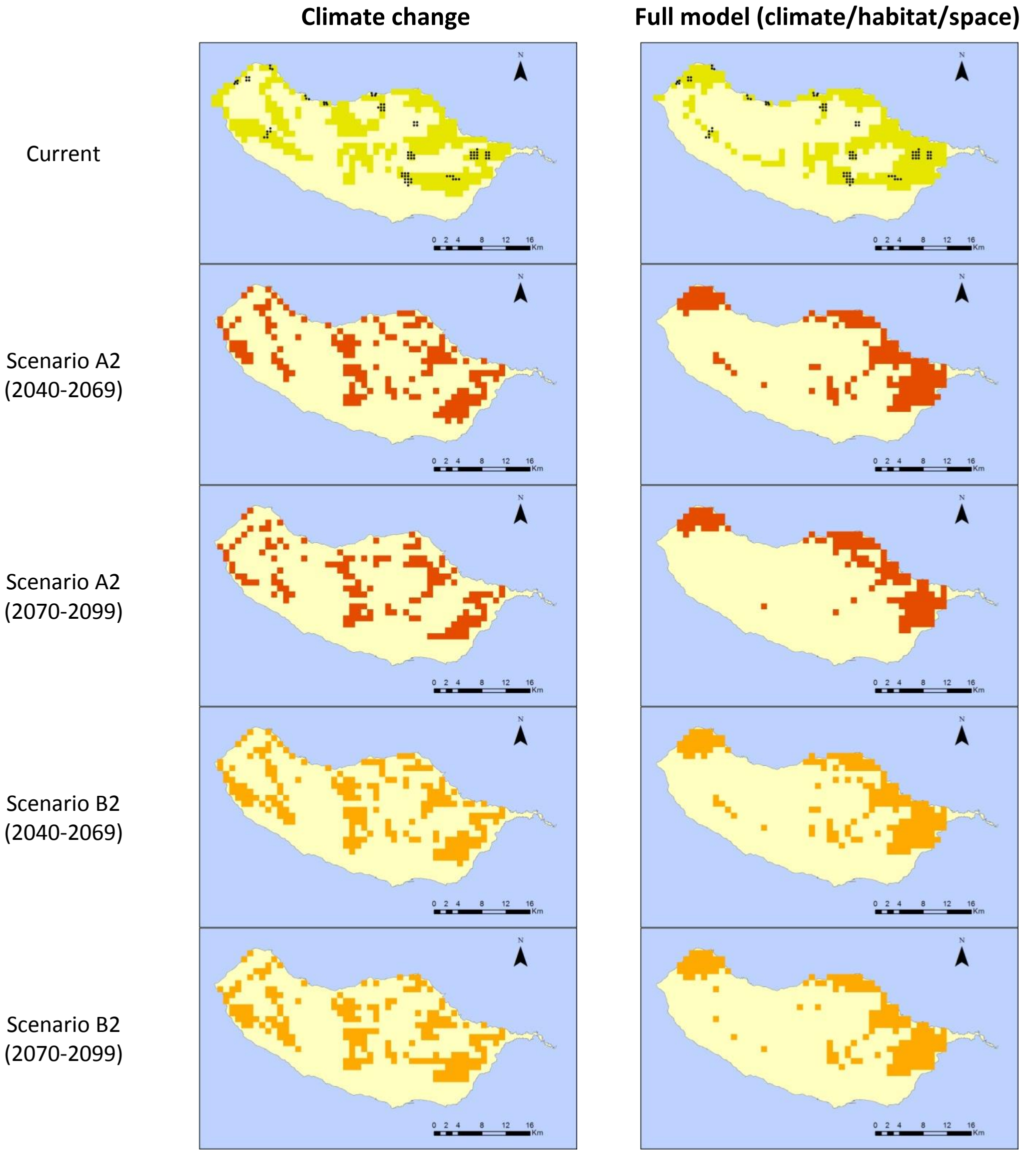

Figure 36: Predictive distribution maps for *Actinella fausta*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Actinella armitageana is only known from the summit ridges around Pico do Areeiro and Pico Ruivo, in the central part of the Island. Found in bunch grasses around small crags at 1200-1800 meters high, this vulnerable species has a small extent of occurrence (Figure 37). Our climate model identified suitable areas for *A. armitageana* in the surroundings of the known current distribution, and in the western plateau of the island, at lower altitudes; however, predictions under A2 and B2 scenarios indicate a considerable reduction of species range, up to 100% (A2 scenario). According to the full model, *A. armitageana* is manly influenced by presence of herbaceous vegetation and shrub areas, longitude and temperature. Although our full model has identified suitable areas for the species distribution at lower altitudes, future predictions indicate a notable decrease in species range (with possible extinction in both scenarios).

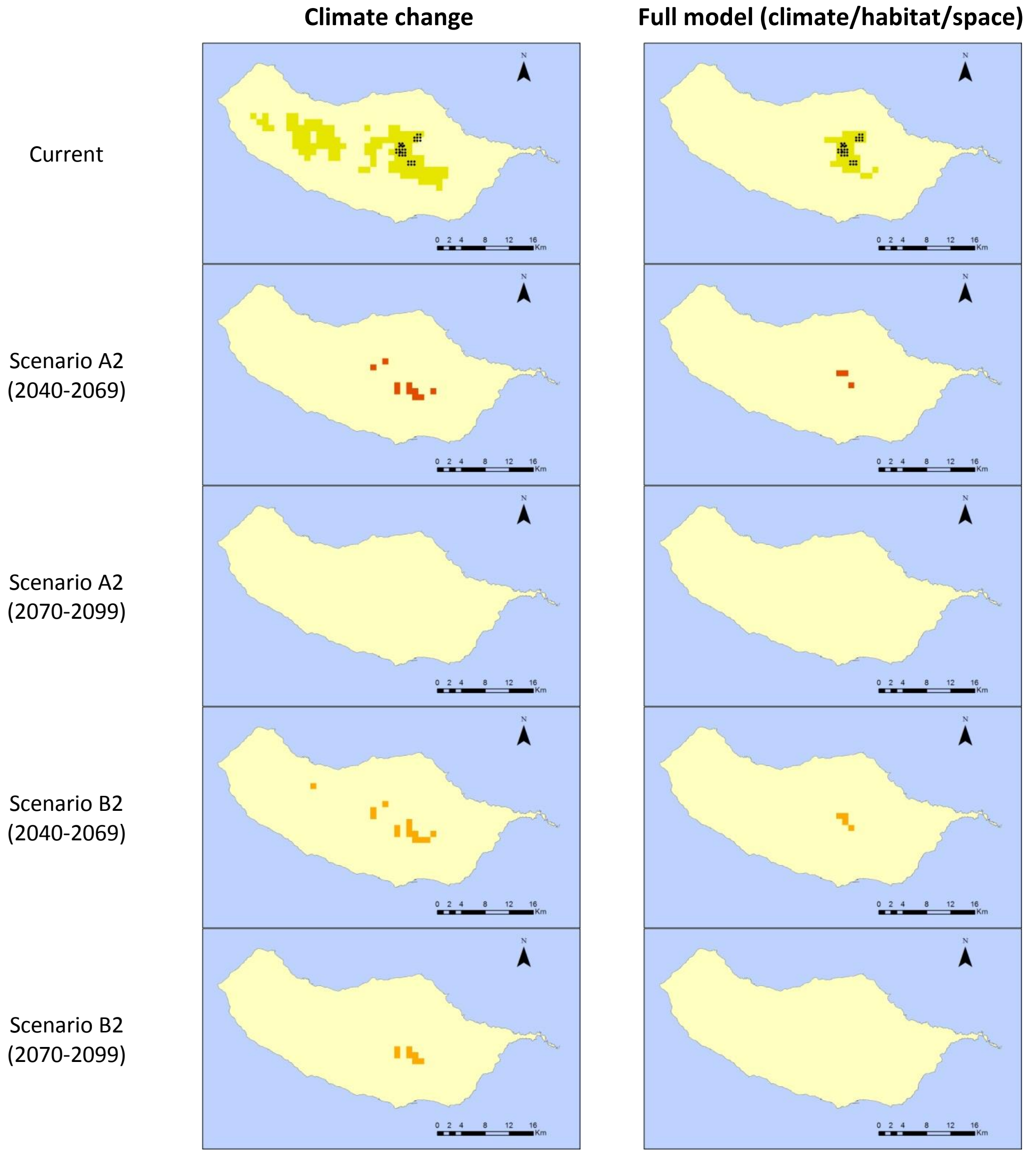

Figure 37: Predictive distribution maps for *Actinella armitageana*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Found at intermediate and high elevations in Laurel forest, *Leptaxis furva* is found at the base of the trees and among leaf-litter on rock crags. Assumed to live at low density, no recent data on *L. furva* population trends is known. Our climate model identified adequate climatic niches for this species in the surroundings of known areas, especially in the central and western part of the island (Figure 38). In the next years, an increase of suitable area is expected. According to the full model, *L. furva* is highly influenced by the presence of natural forest, precipitation, presence of herbaceous vegetation and space (both latitude and longitude). The model suggests that suitable areas might increase.

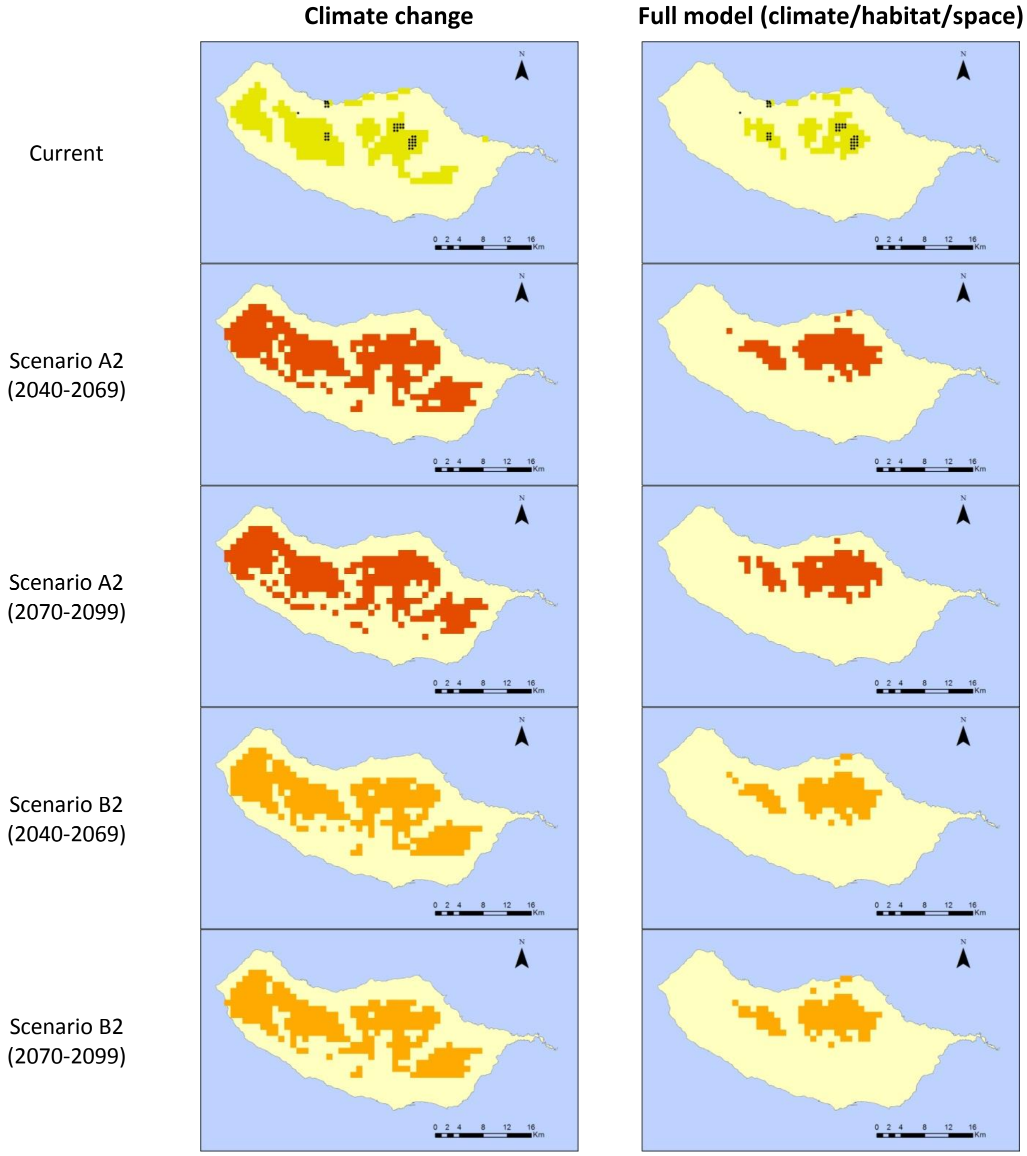

Figure 38: Predictive distribution maps for *Leptaxis furva*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

Leptaxis membranacea has a wide distribution in the island, and is normally found in shady valleys and ravines at intermediate and higher elevations, within Laurel forest.

New potential distribution areas were recognized by our climate model (Figure 39); nonetheless future scenarios suggest that suitable climate might decrease area (up to 60% in A2 scenario). According to the full model, longitude, presence of forested areas and latitude are the key factors in *L. membranacea* distribution. Future scenarios suggest a considerable reduction on suitable habitat for the species, up to 50% in A2 scenario.

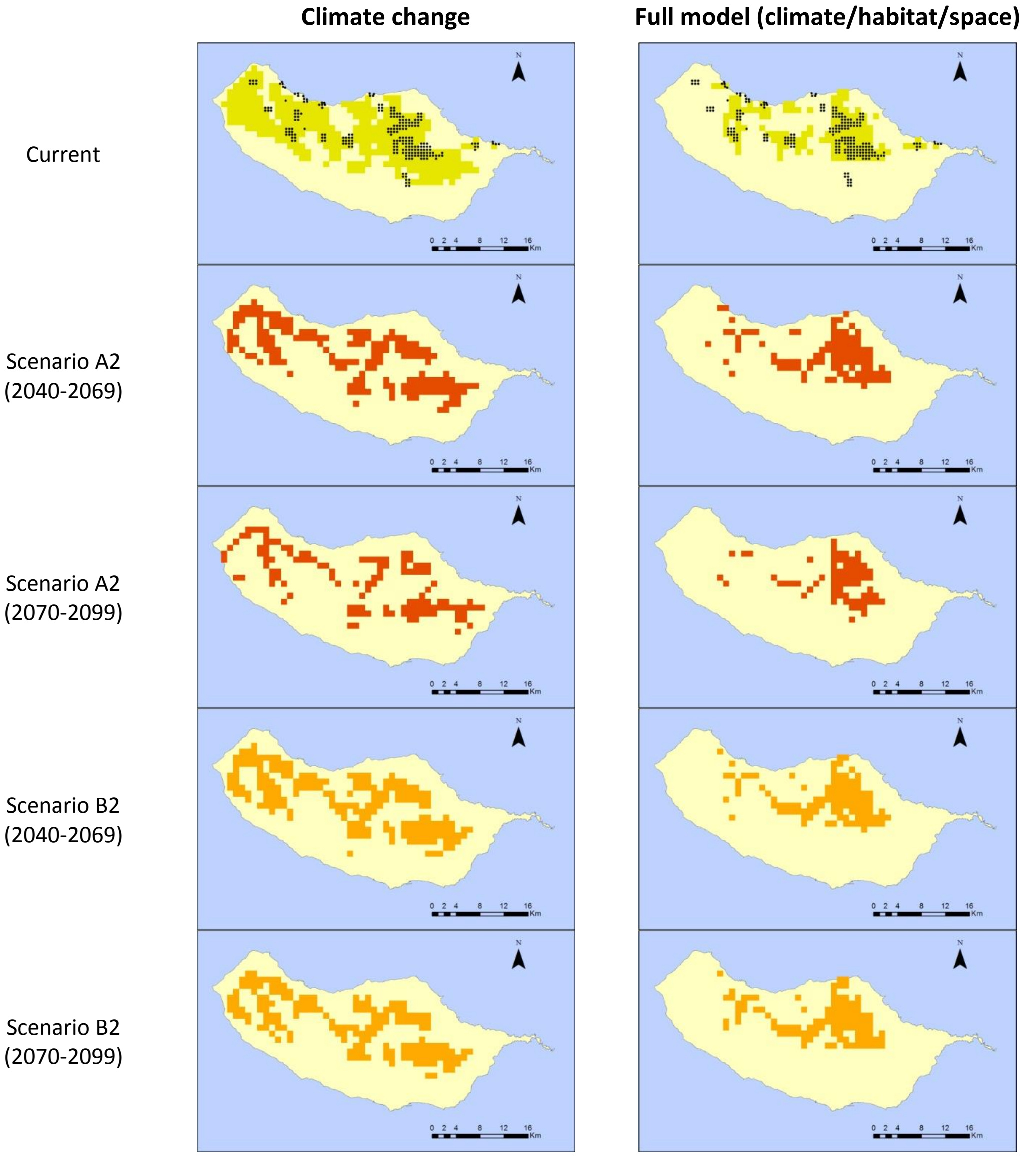

Figure 39: Predictive distribution maps for *Leptaxis membranacea*. On the first row, black points represent occurrence data, and green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of the species under future climatic and habitat change scenarios (red for A2 and orange for B2).

3.4. Overall patterns of change

In both sets of models, there is great variability among species to projected climate or climate/habitat change. Table 2 summarises the trends under the pure climate change scenarios, and Table 3 does the same for the mixed climate/habitat/geography model.

Within the climate-only models, for low emissions scenario (B2), 70.97% of the species included showed a consistent decline in climatically suitable area, while 22.58% of the species are predicted to have a larger distribution. One species, *Leiostyla heterodon*, is inclusively expected to have no suitable areas in the future. For the high emissions scenario (A2), a higher reduction of suitable climate is expected, with 80.65% of the species predictably experimenting smaller suitable areas. Roughly 19% of the species are predicted to increase their distributions (Table 2).

It is worth mentioning that, according to the A2 scenario, four species listed as endangered by the IUCN, *Leiostyla heterodon* (VU), *Actinella armitageana* (VU), *Leiostyla falknerorum* (EN), *Geomitra tiarella* (EN), and one listed as of least concern, *Leiostyla irrigua* (LC), may lose all suitable area, until the end of the century (Figure 40). Vulnerable species, such as *Actinella actinophora*, *Craspedopoma lyonnetianum*, *Leiostyla arborea*, *Leiostyla laurinea* and *Plutonia albopalliata* are also foreseen to occupy smaller areas, in both periods.

Comparatively, the full model predictions, including climate and habitat changes and geography, probably allowed a more accurate estimation of future habitat suitability. Under the B2 scenario, was noticed that 32.26% of the species are predicted to increase their distribution, while 67.74% show reductions on their suitable areas (Table 3). The species reducing their areas include the *Endangered Geomitra tiarella*, *Leiostyla concinna* and *Leiostyla falknerorum* (up to 90% of the current range for *L. concinna*). The species listed as *Vulnerable Actinella actinophora*, *Actinella armitageana*, *Craspedopoma lyonnetianum*, *Leiostyla colvillei* and *Leiostyla heterodon*, also exhibit a negative tendency in their future suitable areas. By contrast, positive trends are foreseen for the *Critically Endangered Actinella arridens*, and a few *Vulnerable* species, such as *Leiostyla arborea*, *Leiostyla laurinea*, *Leptaxis furva* and *Plutonia albopalliata*. The Least Concern *Craspedopoma trochoideum* may increase roughly 75% of its suitable area by the end of the century.

For the high emissions scenario (A2), a decrease of suitable climate is expected for 70% of the species, whereas 25.81% of the species will experience an increase in suitable areas. The remaining species showed no clear tendency, exhibiting both expansion and reduction depending on the time period. In this scenario some species listed as *Endangered* by the IUCN, such as *Geomitra tiarella*, *Leiostyla concinna* and *Leiostyla falknerorum*, are expected to decrease their suitable areas by the end of the century (with the possible extinction of *L. concinna*). A species listed as *Vulnerable*, *Actinella armitageana*, might also be driven to extinction, and *Actinella actinophora*, *Craspedopoma lyonnetianum* and *Leiostyla colvillei*, all *Vulnerable*, are also foreseen to occupy smaller areas in both periods. With an opposite patterns, major increases of up to 90% have been predicted for *Actinella arridens* and *Craspedopoma trochoideum*.

Among the 31 species considered, the trends shown in both models are the same for 23 species (19 a consistent decrease in potential range, four an increase). Six species show different trends in the two models and two show inconsistent changes within models according to scenario.

Species	IUCN status	Current	A2		Tendency	B2		Tendency
			2040-69 (km^2)	2070-99 (km^2)		2040-69 (km^2)	2070-99 (km^2)	
Leiostyla heterodon	VU	9	0	0	Reduction/Extinction	0	0	Reduction/Extinction
Leiostyla falknerorum	EN	33	24	0	Reduction/Extinction	27	13	Reduction
Geomitra tiarella	EN	99	25	0	Reduction/Extinction	30	49	Reduction
Actinella actinophora	VU	112	95	54	Reduction	96	87	Reduction
Actinella armitageana	VU	118	10	0	Reduction/Extinction	14	7	Reduction
Leiostyla vincta watsoniana	LC	120	162	168	Expansion	156	181	Expansion
Leiostyla irrigua	LC	131	21	0	Reduction/Extinction	23	11	Reduction
Leiostyla arborea	VU	135	113	78	Reduction	141	134	No trend
Leiostyla concinna	EN	156	31	5	Reduction	42	23	Reduction
Leiostyla vincta vincta	LC	156	128	120	Reduction	119	137	Reduction
Actinella arridens	CR	157	230	257	Expansion	214	208	Expansion
Leiostyla colvillei	VU	176	270	282	Expansion	251	243	Expansion
Lauria fanalensis	LC	176	141	130	Reduction	134	116	Reduction
Craspedopoma trochoideum	LC	185	402	455	Expansion	388	409	Expansion
Leiostyla cassida	CR	192	115	77	Reduction	135	146	Reduction
Leiostyla furva	VU	193	280	275	Expansion	275	272	Expansion
Boettgeria crispa	NT	205	106	45	Reduction	127	109	Reduction
Plutonia albopalliata	VU	205	203	152	Reduction	227	221	Expansion
Leiostyla sphinctostoma	LC	215	208	210	Reduction	216	204	Reduction
Craspedopoma lyonnetianum	VU	242	54	10	Reduction	68	45	Reduction

Plutonia behnii	LC	259	209	153	Reduction	238	227	Reduction
Actinella fausta	LC	268	172	149	Reduction	196	194	Reduction
Plutonia nitida	LC	273	195	106	Reduction	218	190	Reduction
Craspedopoma neritoides	LC	287	367	323	Expansion	368	365	Expansion
Leiostyla cheilogona	LC	290	233	227	Reduction	251	249	Reduction
Leiostyla laurinea	VU	294	231	135	Reduction	237	206	Reduction
Leptaxis membranacea	LC	323	178	123	Reduction	206	181	Reduction
Leiostyla loweana	LC	351	330	312	Reduction	342	353	No trend
Plutonia marcida	LC	373	267	200	Reduction	291	283	Reduction
Craspedopoma mucronatum	LC	382	344	287	Reduction	362	362	Reduction
Plutonia ruivensis	LC	416	298	199	Reduction	327	319	Reduction

Table 2: Land snails species list, conservation status under the IUCN criteria (LC – Least Concern, NT – Near Threatened, VU – Vulnerable, EN – Endangered, CR – Critically Endangered) and area (km^2) where each species is predicted to have suitable climate for each scenario (climate change only, with no habitat change or dispersal limitation).

Species	**IUCN status**	**Current**	**A2**		**Tendency**	**B2**		**Tendency**
			2040-69 (km^2)	**2070-99 (km^2)**		**2040-69 (km^2)**	**2070-99 (km^2)**	
Leiostyla heterodon	VU	8	0	0	Reduction/Extinction	0	0	Reduction/Extinction
Leiostyla colvillei	VU	12	10	1	Reduction	9	3	Reduction
Actinella armitageana	VU	32	3	0	Reduction/Extinction	4	0	Reduction/Extinction
Leiostyla cassida	CR	38	29	24	Reduction	29	24	Reduction
Leiostyla falknerorum	EN	44	42	32	Reduction	42	30	Reduction
Leiostyla concinna	EN	45	6	0	Reduction/Extinction	7	5	Reduction
Leiostyla vincta vincta	LC	46	39	39	Reduction	40	44	Reduction
Geomitra tiarella	EN	48	24	13	Reduction	28	33	Reduction
Leiostyla arborea	VU	70	85	89	Expansion	80	77	Expansion
Leiostyla furva	VU	80	104	103	Expansion	102	99	Expansion
Leiostyla laurinea	VU	83	93	81	No trend	94	92	Expansion
Actinella arridens	CR	86	139	164	Expansion	127	117	Expansion
Leiostyla vincta watsoniana	LC	86	80	72	Reduction	77	83	Reduction
Plutonia behnii	LC	95	70	57	Reduction	73	70	Reduction
Leiostyla irrigua	LC	98	48	22	Reduction	53	44	Reduction
Actinella actinophora	VU	101	66	42	Reduction	65	53	Reduction
Boettgeria crispa	NT	101	66	43	Reduction	71	63	Reduction
Leiostyla cheilogona	LC	101	85	74	Reduction	86	86	Reduction
Craspedopoma lyonnetianum	VU	105	93	94	Reduction	92	85	Reduction
Craspedopoma trochoideum	LC	112	199	216	Expansion	194	195	Expansion

Leiostyla loweana	LC	133	133	129	Reduction	138	136	Expansion
Plutonia albopalliata	VU	133	159	162	Expansion	160	157	Expansion
Craspedopoma neritoides	LC	138	157	141	Expansion	153	140	Expansion
Plutonia marcida	LC	140	82	46	Reduction	91	84	Reduction
Leptaxis membranacea	LC	142	103	72	Reduction	106	107	Reduction
Leiostyla sphinctostoma	LC	147	166	230	Expansion	161	182	Expansion
Lauria fanalensis	LC	158	225	243	Expansion	209	215	Expansion
Plutonia nitida	LC	160	117	70	Reduction	122	112	Reduction
Craspedopoma mucronatum	LC	196	166	134	Reduction	180	178	Reduction
Plutonia ruivensis	LC	200	125	72	Reduction	136	127	Reduction
Actinella fausta	LC	227	157	132	Reduction	169	157	Reduction

Table 3: Land snails species list, conservation status under the IUCN criteria (LC – Least Concern, NT – Near Threatened, VU – Vulnerable, EN – Endangered, CR – Critically Endangered) and area (km^2) where each species is predicted to have suitable habitat for each scenario (climate plus habitat change with dispersal limitation).

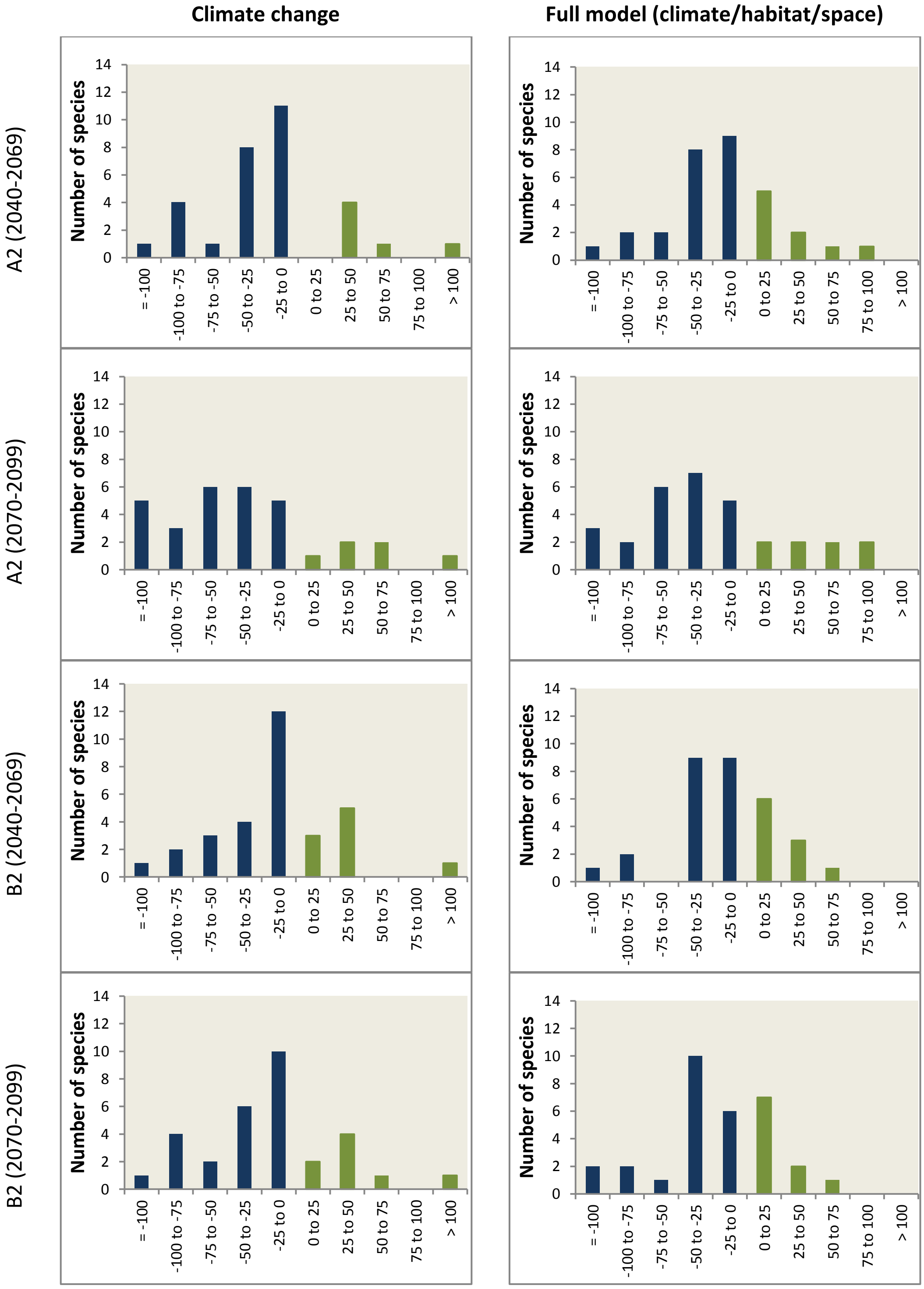

Figure 40: Number of species predicted to gain or lose suitable habitat under A2 and B2 scenarios (left: climate change model; right: climate and habitat change model), categorized by the percentage of range reduction/expansion relatively to present. Blue columns represent species predicted to lose suitable climate/habitat while green columns represent species predicted to gain suitable climate/habitat.

3.5. Net change versus turnover

The analysis of change presented above is based on simple cell-counts. Change or stability in the number of appropriate cells can arise in different ways. At one extreme, a loss or gain may arise from a single process; at the other, a net result may arise from the difference between many losses and gains over the period in question. Dortel *et al.* (2013), point out that while an estimated decrease indicates a threat, even if known populations are not predicted to fail, an increase is only beneficial if the species is able to colonise what has become available. Hence, especially for slow-moving animals with poor dispersal capacity, an increase caused by a great turnover of suitable sites may not prevent losses. If there are barriers to dispersal, previously occupied cells may become unsuitable while new ones may not be possible to be colonized in relatively short time-frames (Figure 41).

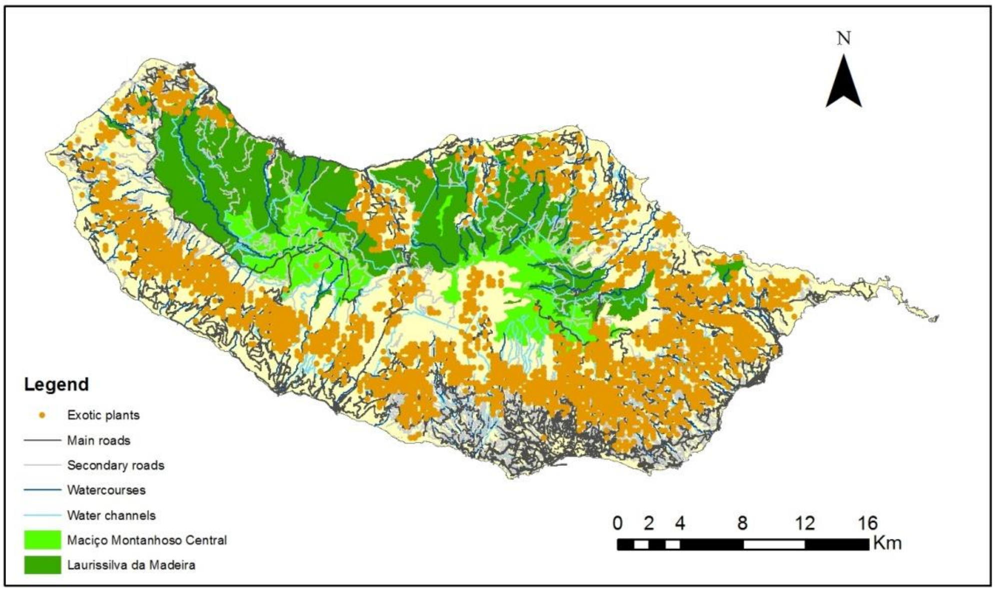

Figure 41: Environmental barriers that might limit land snails dispersion.

In general, models under climate change-only suggest wider future ranges than those including also habitat and spatial variables. In general, the difference between future and current area, reflect a negative tendency amongst the analysed models (Figure 42). While there are changes in potential distribution in both directions, as described above, losses are somewhat more common in all scenarios and datasets. In fact, such losses are even more common among very restricted species, which are expected in almost every case to decrease their suitable areas (Figure 42, see species with current areas inferior to 60 km^2.

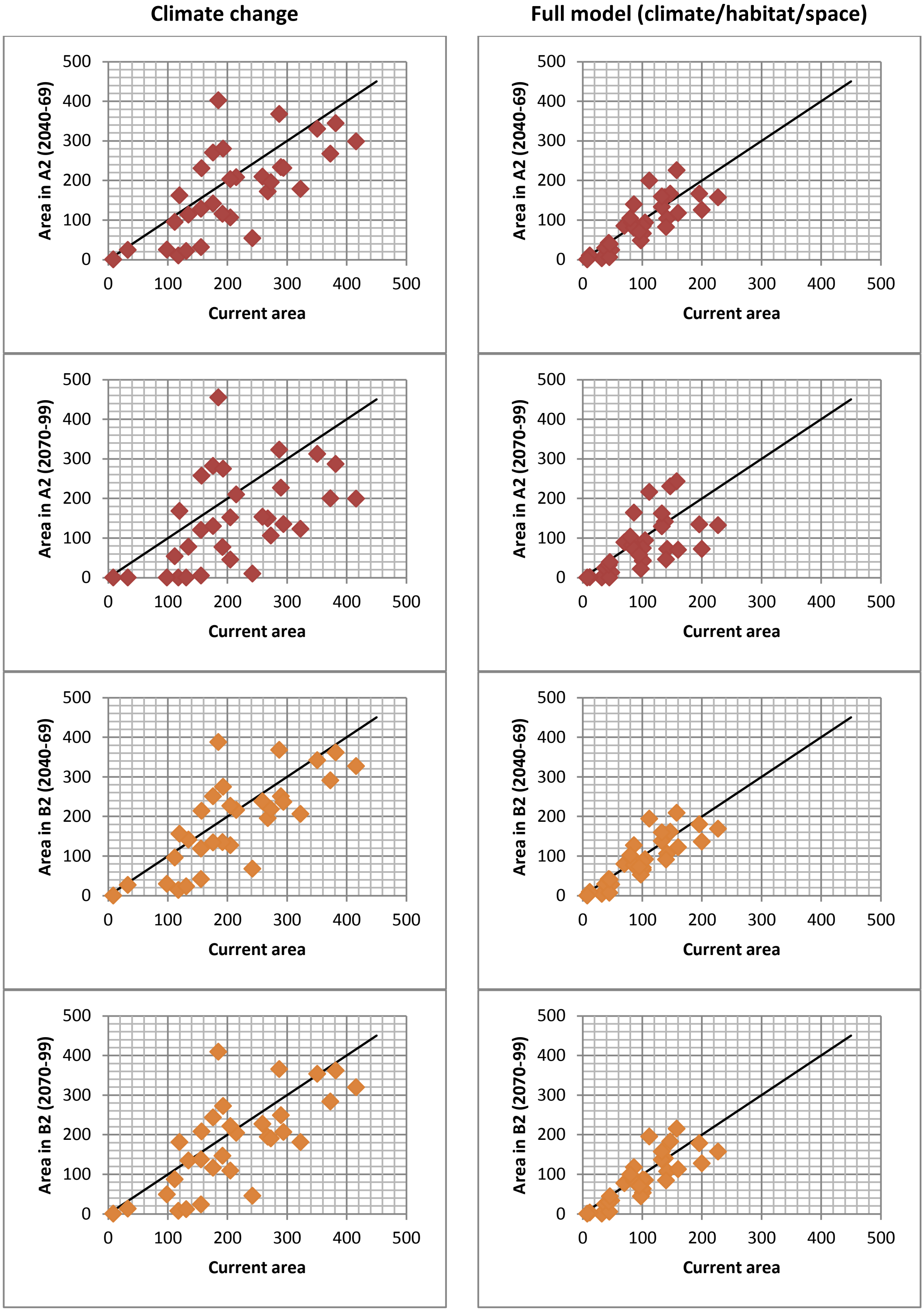

Figure 42: Changes in area (number of grids cells) between present and future (A2 and B2 scenarios, and periods 2040-69 and 2070-99). On the left side are presented models under climate change; on the right models under climate and vegetation change). Each dot represents a species. The diagonal lines represent an hypothetical situation of no change, where present and future areas are similar. Dots above and below the line represent species where an increase or decrease in area is expected, respectively.

3.6. Changes in community composition

Changes in the diversity of land snail assemblages are considered here in two ways. How do predicted changes affect the potential species richness in any grid square (alpha diversity), and how do the faunas of any cell differ in composition over time (beta diversity).

The map of predicted *Alpha-diversity* (species richness), derived from the overlay of individual distribution maps, showed different patterns for the model under climate change only and the one including climate, habitat and space, in all scenarios and time periods (Figure 43). It is worth noting that the figure deals only with species included in this work; a value of 0 does not indicate a total absence of snails.

While climate-only projections suggest a wider distribution of species-rich sites, stretching from west to east, the full model clearly reflects the influence of geographic variables, especially longitude, and the presence of forested areas. Species richness achieved maximums values of 23 for climate modelling, mainly concentrated in sites with low-temperature and high precipitation and humidity. For the full model, a maximum value of 25 species was recorded, with a significant concentration of species in the central part of the island at high elevations. Species richness, for both future time periods and scenarios shows a slight northward movement from the central part of the island and a decrease (A2 scenario: maximum value of 19; B2 scenario (2040-2069): maximum value of 19; and B2 scenario (2070-2099): maximum value of 21), when compared to the present (maximum value of 25 species).

Changes in *Alpha-diversity* over time were similar for the full model (range -20 to +13) and for climate alone (-19 to +16). Negative values represent species loss, while positive values correspond to species gain. Major losses are expected to occur in both scenarios for the climate model. According to this model, losses will mainly occur at high altitude areas along the entire island (Figure 44). Gains are predicted to occur at intermediate elevations, particularly on the southern/western slopes of the island.

On the full model, and although species richness is concentrated in the highest elevations of the island, less clear tendencies are observed in *Alpha-diversity difference*s patterns. Again, major losses seem to occur between the future periods and the present (2040-69 vs. current and 2070-99 vs. current), especially in such region.

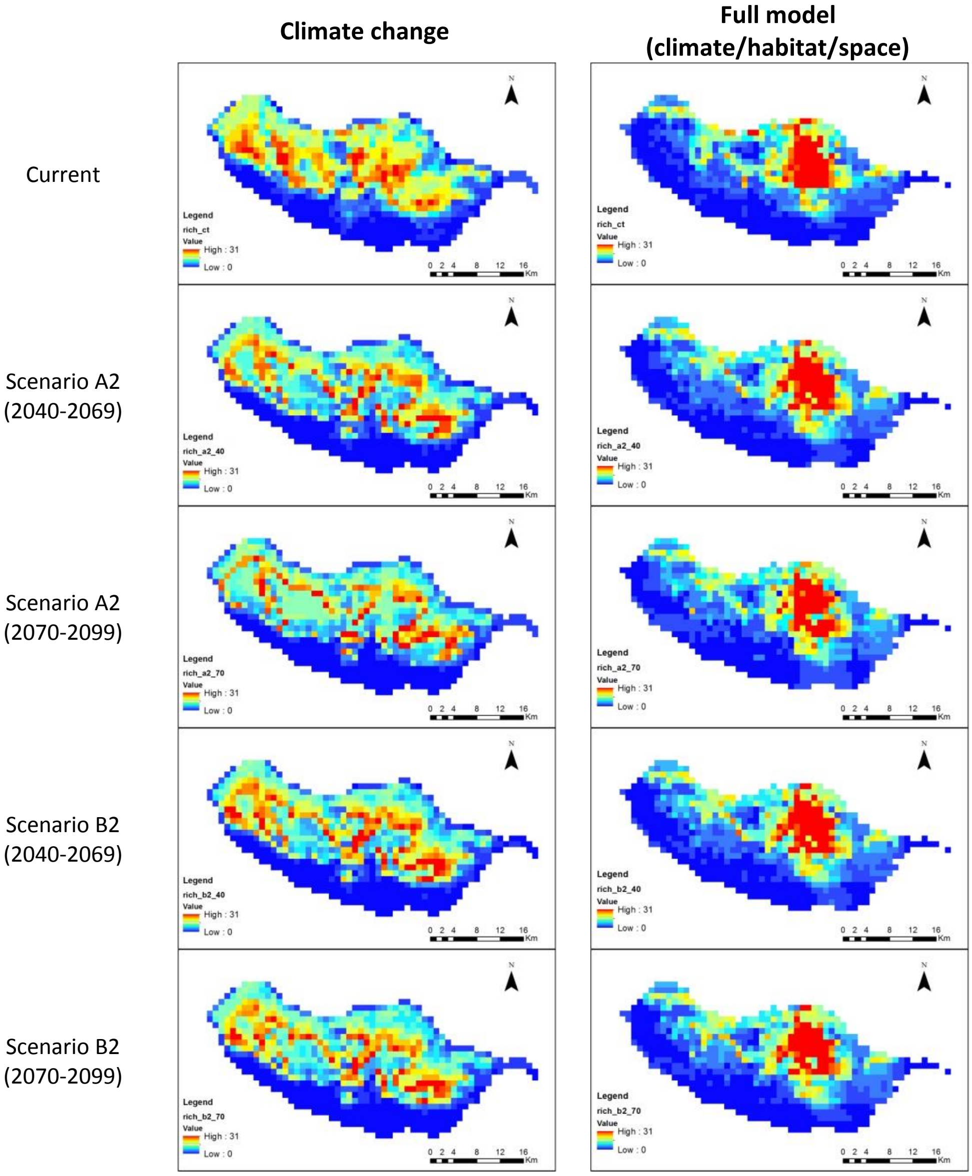

Figure 43: Estimated distribution of land snails' species richness (*Alpha-diversity*). *Alpha-diversity* values, calculated under climate change scenarios, are presented on the left side; on the right side is represented *Alpha-diversity* under the full model (climate/habitat/space), for 2040-69 and 2070-99 periods.

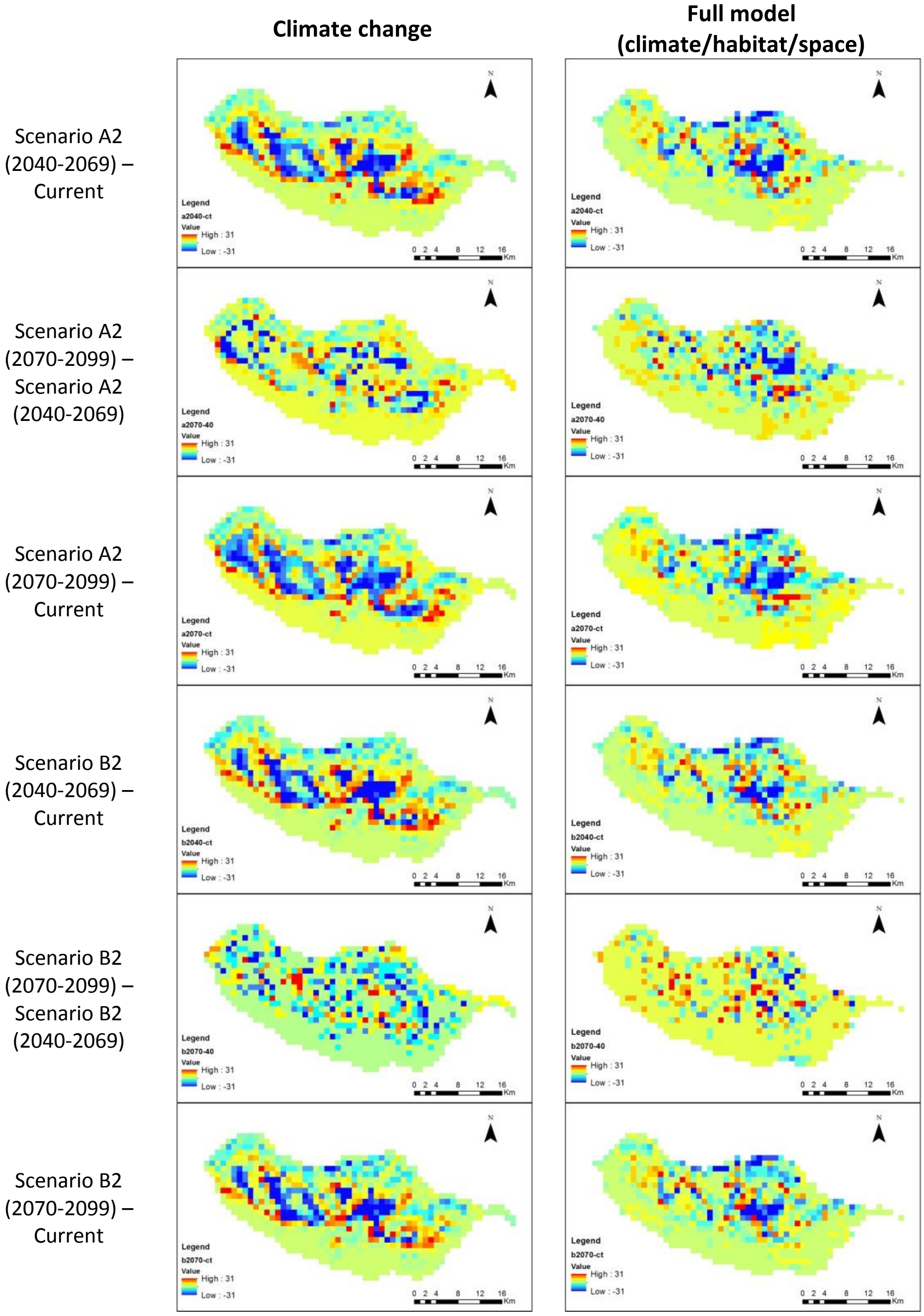

Figure 44: Geographical distribution of *Alpha-diversity differences* among the analysed periods. *Alpha-diversity differences*, calculated under climate change scenarios, are presented on the left side; on the right side are represented under the full model (climate/habitat/space), for 2040-69 and 2070-99 periods.

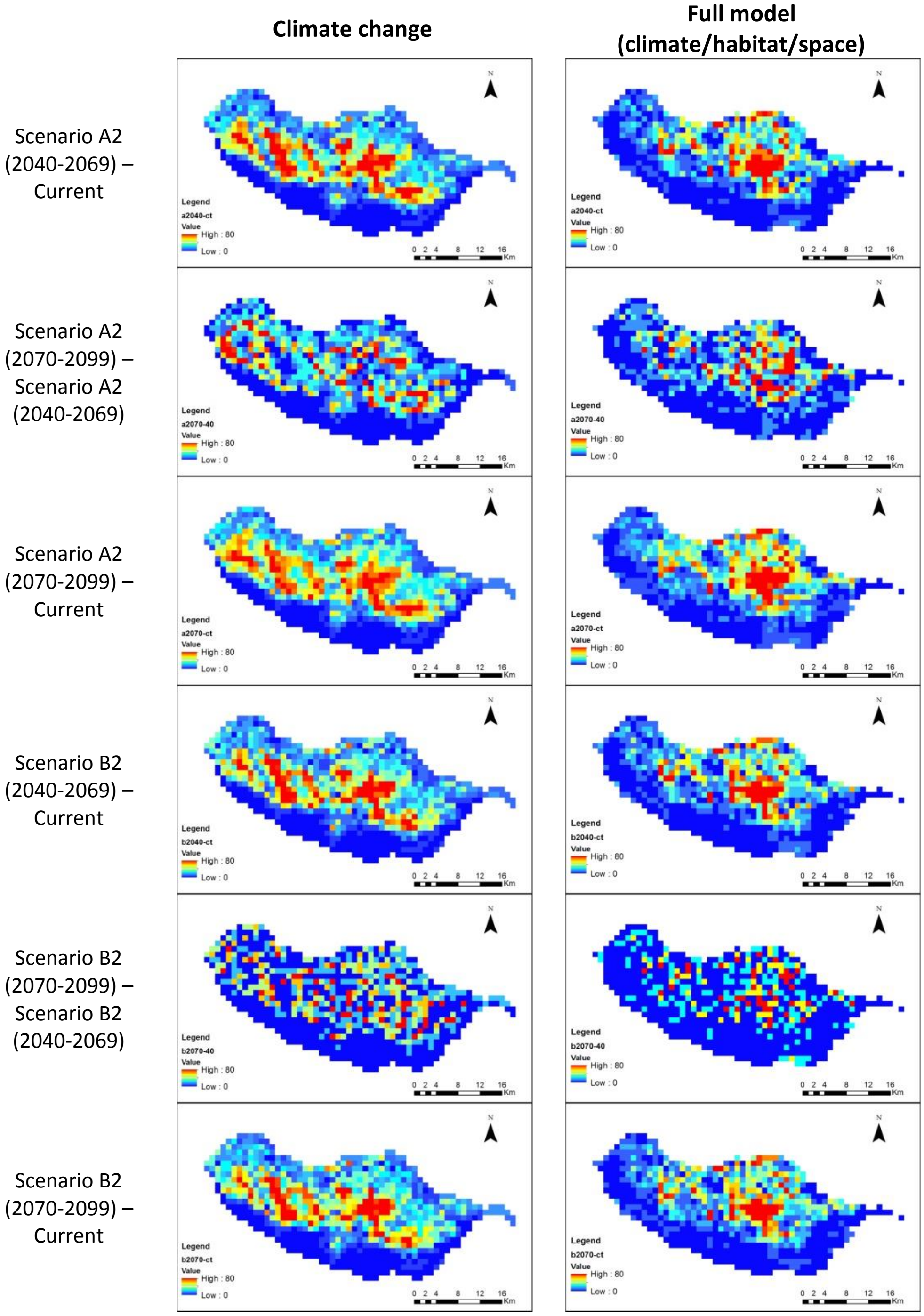

Figure 45: Geographical distribution of *Total Beta-diversity* among the analysed periods. *Beta-diversity* values, calculated under climate change scenarios, are presented on the left side; on the right side are represented values under the full model (climate/habitat/space), for 2040-69 and 2070-99 periods.

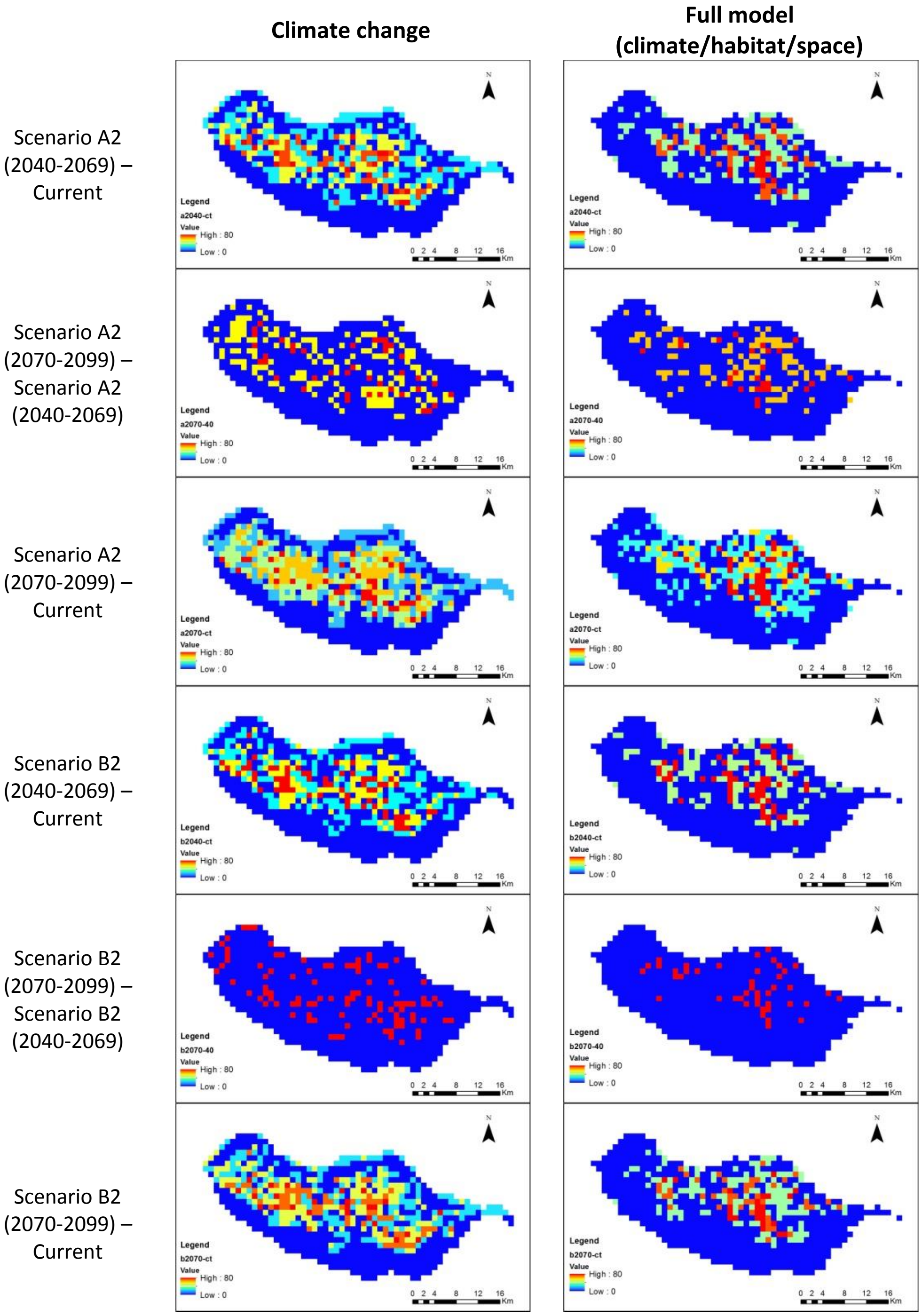

Figure 46: Geographical distribution of *Beta diversity* due to *Species replacement* among the analysed periods. *Species replacement* values, calculated under climate change scenarios, are presented on the left side; on the right side are represented values under the full model (climate/habitat/space), for 2040-69 and 2070-99 periods.

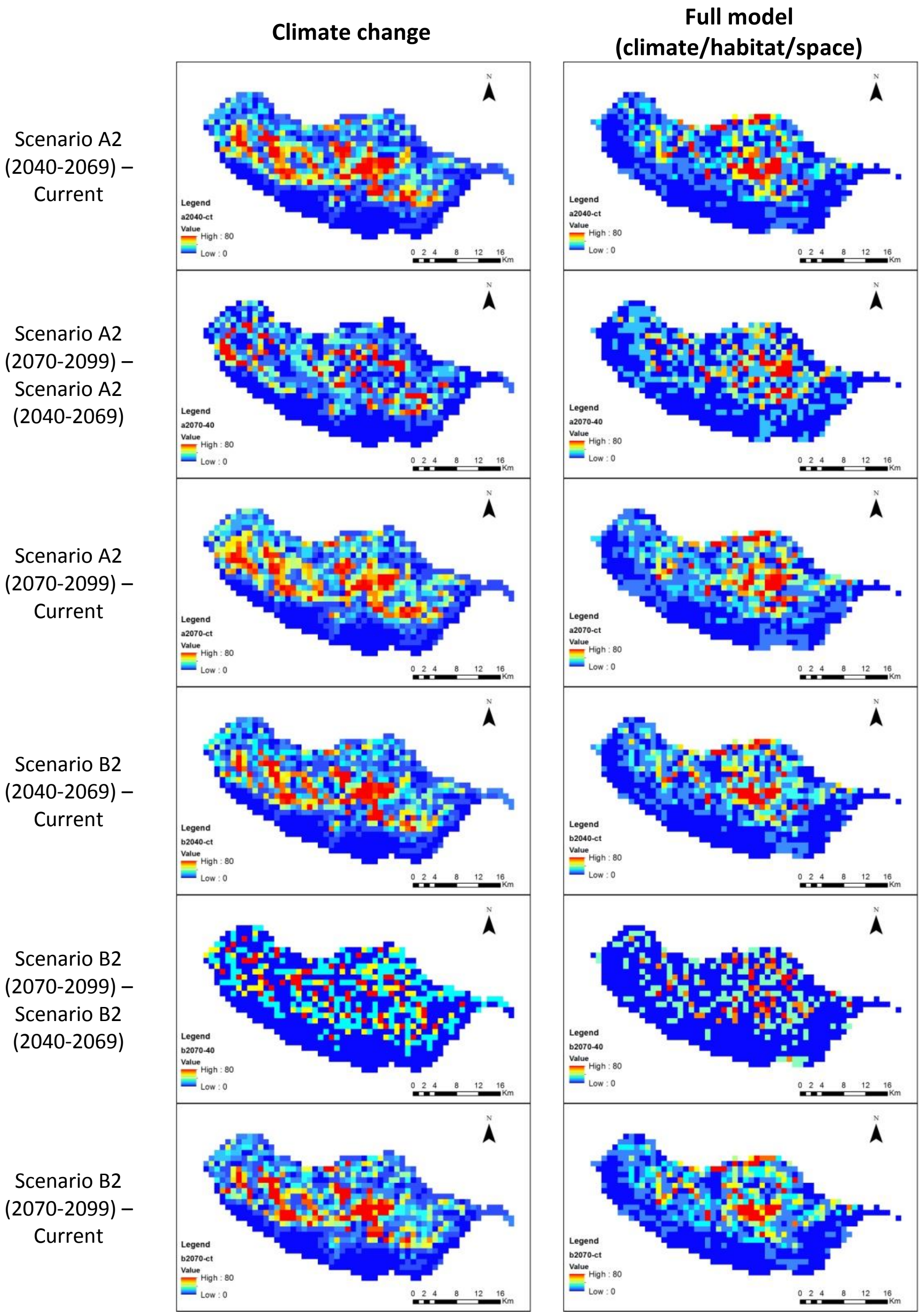

Figure 47: Geographical distribution of *Beta diversity* due to the *Species richness difference* among the analysed periods. *Species richness difference* values, calculated under climate change scenarios, are presented on the left side; on the right side are represented values under the full model (climate/habitat/space), for 2040-69 and 2070-99 periods.

According to the climate model, total *Beta-diversity* is highest in the high elevation areas stretching from west to east (Figure 45). This pattern is mainly driven by β_{rich} (Figure 47), revealing a large species loss at high elevations (see also Figure 44). β_{-3}, derived from species replacement (Figure 46), does not show a clear pattern, although it seems maximum at intermediate altitudes, probably driven by mid-altitude species substituting high altitude species in the future at such elevations.

The full model, including habitat and dispersal limitation, shows similar trends as the climate model but with high values only for the central/eastern part of the island, where most species richness is concentrated. It is worth noting for both models that large areas, especially in the south, that show very little change are not occupied by the species considered here, or do not have inventories entered into BIOBASE. Effectively, they are areas unsuitable for the species both at present and under any scenario of climatic change.

4. DISCUSSION

4.1. The Madeiran land mollusc fauna at present

Defined as a biodiversity hotspot with many endemic species (Médail and Quézel, 1999; Myers *et al.*, 2000; Mittermeier *et al.*, 2005), the Madeira archipelago is, like other oceanic archipelagos very vulnerable to the effects of climate change (Malcolm *et al.*, 2006).

Within the island, the Laurel Forest of Madeira encloses important communities of endemic land snails many of which are confined to this habitat. In the last five years, this habitat has been damaged by violent fires that destroyed a vast extension of forest and alpine vegetation (also in Maciço Montanhoso Central), decreasing the abundance of land snails within the study area. This is only the latest series of events to threaten snail species; early records show that distributions were wider before development and forest clearance.

Like other invertebrates with low dispersal abilities, molluscs are, in many cases, the first to become extinct in response to habitat loss and disturbance. Climate change imposes an additional stress. There is a lack of information about the real impacts of climate changes on this group (neglected by IUCN assessments), in addition to their exclusion from most conservation efforts and biodiversity monitoring. Hence the urgency of this study, which represents the most extensive assessment on the projected impacts of climate change on species of conservation concern for the Madeira archipelago. However, in considering the results of the study, some limitations must be considered.

4.2. Limitations to the effectiveness of the modelling process

Any model depends for its effectiveness on the quality and quantity of the data used. Although Madeira has been intensively surveyed for land molluscs, not all data are reliable and some taxonomic issues are unresolved. While only the most reliable data have been used in this study, some errors probably remain. Within the *Laurissilva*, the eastern parts of this habitat have been surveyed at far greater intensity than those from further west. The BIOBASE data set does not yet cover the whole island at the resolution of grid cells used in this study. The known distribution of each species is likely to be considerably smaller than that actually occupied. This incompleteness in the data is illustrated by the fact that my own sampling, done in rather unfavourable dry conditions provided 19 new records for 11 of the target species (*Actinella actinophora*, *Actinella* *armitageana*, *Boettgeria crispa*, *Craspedopoma troichoideum*, *Craspedopoma neritoides*, *Craspedopoma mucronatum*, *Leptaxis furva*, *Leptaxis membranacea*, *Plutonia marcida*, *Plutonia nitida* and *Plutonia ruivensis*).

The topography of Madeira is extreme, with many vertical or near vertical surfaces of different aspects within the area encompassed by the grid scale used. The range of altitude within each cell may also be great. The exact conditions applying to a particular sample may not reflect the mean or median values for the cell. Hence, the estimates of present and future climate and habitat in terms of their suitability for any one species are necessarily very approximate. Interpretation of trends must take these limitations into account.

Despite these limitations, the climate change alone model shows a consistent pattern when present potential range is considered. With very few exceptions, the present potential range is much greater than that actually known. While this may reflect in part the lack of data, it is clear that climate alone is not the only determinant of present ranges. The full model attempts to overcome this problem by incorporating habitat and geographical variables into the constraints applied in the model. Because of human interference, not all climatically suitable areas are occupied by laurel forest. Even with the addition of habitat availability, it is apparent that there are geographical constraints on the distribution of some species, presumably as a result of dispersal limitation and local evolutionary events, coupled with some regional extinctions associated with past climate change and human activity. While latitude and longitude may not reflect these geographical constraints precisely, they do limit the projected changes in distribution under climate change scenarios taking into account the limited powers of dispersal shown by most land molluscs. Thus, while the full model represents a more realistic assessment of possible future changes in distribution, it is important to note that all outputs refer to potentially suitable areas for each species. In practice, both models show a general similarity in trends over time.

4.3. Model outputs and projected distributions

Earlier work on land snail faunas (Cook *et al.*, 1990; Cameron and Cook, 1997) shows that the Laurel forest has a distinctive fauna. The cool and humid environment (Sjögren, 1972), makes *Clethro-Laurion* forest the perfect habitat for thin-shelled species and semi-slugs (Cameron and Cook, 1997). Our model confirms that situation, identifying forest species as highly dependent of humidity and precipitation levels, also previously stated by Teixeira (2009). Although forest faunas do not show any great geographical differentiation (Cameron and Cook, 1997), there is some altitudinal differentiation with some species being restricted to higher elevations that are concentrated in the east-central part of the island.

The Maximum entropy model identified new potential distribution areas for all species and was able to project future suitable areas for endemic and threatened species of Madeira Island. Widely used in monitoring and conservation policies, species distribution models (SDM) can be applied in the evaluation of potential impacts of climate change in species range size, community patterns (such as richness, diversity and turn-over), and representation in Protected Areas (Velásquez-Tibatá *et al.*, 2013).

According to the obtained results, suitable areas might shift under climate change, in every analysed scenario. Two categories of species can be distinguished: the “declining” species and the “successful” species. According to climatic model, *Leiostyla heterodon* (VU) will be one of the most affected species, losing all the suitable climate sites by the end of the century, in both scenarios. These results indicate that climate change alone may have severe effects on snail distribution over the course of this century, particularly for species highly dependent on precipitation and relative humidity such as *Leiostyla falknerorum* (EN) and *Geomitra tiarella* (EN).

As suggest by Santos and Aguiar (2006), the modelled future scenario on Laurel forest distribution suggests its expansion to higher elevations, with the inherent constriction at lower altitudes; while significant reductions on natural shrub areas and herbaceous vegetation are predicted to occur.The inclusion of new habitat and spatial variables in the full model (three vegetation classes plus latitude and longitude), allowed a more realistic approach to the real impacts of climate change on species distributions. The MaxEnt outputs under the full model returned a slight different behaviour in land snails’ future species range; and when compared to the climate model, less current suitable areas were identified for species distribution. The condition imposed by the vegetation and spatial variables (in addition to climatic variables) resulted in a “restriction” of suitable areas to the surroundings of known occurrence sites. According to the full model, major losses are expected to *Actinella armitageana* and *Leiostyla heterodon*, where 100% of their current suitable areas are predicted to disappear, leading to the possible extinction of both species.

While there are some minor differences between the outputs of the two models, the overall trend is similar in both, indicating substantially more declines (and some possible extinctions) than increases in potentially inhabitable areas. While the data available do not make it possible to detect consistent differences between those species, with increasing or decreasing potential ranges, there is a trend for those at present limited to high altitudes to see decreases. These species (e.g. *Actinella armitageana*, *Leiostyla colvillei* and *Leiostyla heterodon*) are found mainly in the alpine zone, and climate warming will reduce the size of this area.

It should be noted that there are a number of species excluded from our analysis, due to the low number of records. These include IUCN endangered species, such as *Actinella carinofausta* (EN), *Caseolus calvus* (EN), *Geomitra delphinuloides* (CR), *Hemilauria limnaeana* (LC) and *Leiostyla cassidula* (CR). These may also be affected by climate change.

The models indicate the number and position of cells containing potentially suitable sites for each species. Under a regime of climatic and habitat changes, many other variables might influence land snail distribution, such as vegetation, land use, dispersion barriers and perturbation variables. We can note that succession to Laurel forest when an area becomes suitable is not instantaneous, and might take more than a century to complete. For the majority of species, the potential pattern of their future distribution range may involve a significant loss of their current habitats even when the available area shows a nominal increase. With low dispersal capacity, terrestrial molluscs will face major constraints in to order to fight this rapid turnover of favourable areas (Keith *et al.*, 2008). In addition, the connectivity amongst present/current areas is dependent on several landscape characteristics, such as topography, presence of exotic vegetation and disturbed areas, and also internal population dynamics. While widely distributed species such as *Actinella actinophora*, *Actinella fausta*, *Craspedopoma mucronatum*, *Leiostyla cheilogona* and *Leiostyla loweana*, are likely to survive, those with more restricted distributions are at greater risk (Keith *et al.*, 2008). Apart from the high-altitude species mentioned before, species isolated by geographic barriers, such as *Leiostyla concinna*, might face dispersal constraints to other climatically suitable areas.

4.4. Changes in community composition

Studies concerning the impacts of climate change on species distribution often consider that species respond individually to these changes, excluding the importance of community dynamics and interactions between species.

Although some methods combine environmental variables with information about the communities' composition (in order to project more realistic models, that reproduce community dynamics), adapting individual species distributions models to complex biotic interactions is difficult (Araújo and Luoto, 2007; Heikkinen *et al.*, 2007; Baselga and Araújo, 2009).

Community maps, created from the overlay of individual distribution maps, showed different trends under climate change. Suitable areas for many species may shift; and, while some of them might decrease with climate change, some species representation may increase on average. As a result, community composition is expected to change, particularly in the eastern central part of the island, where some areas are predicted to lose a maximum of 20 species, in relation to the current potential species richness.

Alpha-diversity achieved upper values in the full model rather than in the climatic model; and higher species richness values were obtained in the central/northern part of the island at high elevations. According to the climate model, future losses will mainly occur at high altitude areas along the entire island; and gains are predicted to occur at intermediate elevations, particularly on the southern/western slopes of the island.

On the full model, and although higher values of species richness were concentrated in the highest elevations in central/east of the island, less clear tendencies were observed in *Alpha-diversity difference*s patterns. Major changes are expected to occur both in A2 and B2 scenarios and, according to the model, this difference in *alpha* will be concentrated in the eastern central part of the island, were laurel forest is now abundant. However, uncertainty related to communities' dynamics, modeling errors and lack of information on species ecology and interactions has to be considered.

According to our model, both *Alpha-diversity* and *Beta-diversity* differences are expected to occur until the end of the century. To study the underlying community processes and changes in *Beta-diversity* we detached the index into: *Species replacement* (or turn-over) and *Species richness difference*, and evaluated their evolution between the analysed periods (Baselga, 2010; Carvalho *et al.*, 2012).

Changes in *Beta-diversity* patterns are related to the equilibrium between the turnover rate amongst periods, and species richness difference. According to the climate model, and similarly to *Alpha-diversity* values, *Total Beta-diversity* is highest at high elevation areas stretching from west to east. Such pattern is mainly driven by *Species richness difference* revealing a large species loss at high elevations. *Beta diversity* due to *Species replacement*, does not show a clear pattern, although it seems maximum at intermediate altitudes, probably driven by mid-altitude species substituting high altitude species in the future at such elevations. Several studies suggest that alpine habitats are often colonized by range-expanding species and are likely to provide shelter for species shifting north (Peh, 2007; Seimon *et al.*, 2007; Chen *et al.*, 2011; Velásquez-Tibatá *et al.*, 2013), increasing pressure in the new habitat and competition amongst resident species.

The full model, including habitat and dispersal limitation, shows similar trends as the climate model, but with high values only for the central/eastern part of the island, where most species richness is concentrated. Although *Alpha-diversity* maps show a positive trend in some areas, it is important to notice that, frequently, common species contribute more to spatial patterns, rather than rare species (Lennon *et al.*, 2004; Vázquez and Gaston, 2004; Pearman *et al.*, 2010). The definition of guilds and functional traits for land snails would give an important contribute to a better evaluation of the possible community dynamics in response to climate change (Voigt *et al.*, 2007). We also must considerer the fact that habitat and climate are intimately related. As a result, future changes in temperature, precipitation and relative humidity, will induce new pressures in habitat and land use, modifying landscape structure, as we tested in our model.

4.5. From predicted models to conservation

The effective conservation of biodiversity depends on a very specific set of tools related to the analysis of the distribution of species (Araújo and Williams, 2000). Many studies suggest that proactive measures, in order to identify and understand the underlying causes of their trends, are needed to mitigate climate impacts on biodiversity; and predictive models of species distribution coupled with the use of GIS and climate change scenarios have become crucial to identify threats and determine biodiversity vulnerability (Dangermond and Artz, 2010), contributing to species conservation and definition of management strategies (Kareiva *et al.*, 2008).

Supportive information about the general trends in species distribution range, over short (e.g. Green *et al.*, 2008) and long term analysis (e.g. Cordellier and Pfenninger 2009), have been obtained. Nonetheless, a conservative approach to quantitative estimation of species range is appropriate, bearing in mind the limitations inevitable in this first attempt to model the effects of climate change. In particular, we lack information on the dispersal abilities of the species in question. Given their narrow distributions, migration limitations and lack of information about functional traits, dispersal abilities are quite difficult to measure.

Potential ranges in each scenario assume maximal possible dispersal ability for each species, neglecting physical barriers and landscape structure. The real magnitude of the impact of climate change on each species will fluctuate according to their capability to resist to environmental perturbation, and their ability to adjust and recover from habitat changes (Williams *et al.*, 2008; Isaac *et al.*, 2009).

The SDM approach is limited and includes many sources of uncertainty (Webster *et al.*, 2002), such as: a) the uncertainties inherent to the statistical tool used for modelling species distributions; b) the use of global circulation models to predict future climate conditions (Thuiller, 2004; Pearson *et al.*, 2006; Beaumont *et al.*, 2008); c) the uncertainty resultant from scale effects (Seo *et al.*, 2009) and; d) the residual spatial autocorrelation in data, sampling bias and inadequate testing with independent data (Phillips *et al.*, 2009; Veloz, 2009; Merckx *et al.*, 2011). Furthermore, several authors claim that these models generally ignore inter-specific interactions (Davis *et al.*, 1998; Araújo and Luoto, 2007), do not consider long-term population viability (Keith *et al.*, 2008), and the additional challenge of predicting species occurrence in areas with combinations of climate and species composition for which we have no current analog (Elith *et al.*, 2010).

However, recent advances in predictive models suggest that realistic predictions about the consequences of climate change (Araújo *et al.*, 2005b; Huntley *et al.*, 2008) can be obtained from SDMs. They can therefore be applied to assess potential changes in regions where data are not extensive but environments are diverse, and climate predictions have also been improved to obtain better results in smaller spatial scales (Hijmans *et al.*, 2005).

4.6. Land snail conservation

Species resistance to climate change can emerge from four parameters: distribution range, abundance of individuals, adaptive capacity and dispersion ability.

Endemic species ranges are often small, especially those living in oceanic island, making them particularly vulnerable to extinction. With an extremely limited scope for movement in response to environmental change (Whittaker *et al.*, 2001; Gillespie *et al.*, 2008), insular *taxa* may face drastic and irreversible losses. From this point of view, within

Madeira Island, species with narrow distributions such as *Actinella armitageana* and *Leiostyla heterodon* may be more affected by climate change than more widespread *taxa* such as *Craspedopoma mucronatum*, as a result of habitat reduction and the nonexistence of suitable habitat elsewhere in the island. Rather than rare species, locally abundant species might be not so vulnerable to climate changes. Genetic variability and biological traits, such as high reproductive rates, lower age of female sexual maturity and long life span, can provide a potential better adaptation to climatic pressures (Carvalho, 2010).

Although few works have been made in order to determine the adaptive capacity of molluscs and traits of Madeiran species are poorly known, it is possible that some species might adjust their functional and ecological traits towards more favourable climatic conditions (Harte *et al.*, 2004; Bradshaw and Holzapfel, 2006; Parmesan, 2007).

Nonetheless dispersion ability has been recognized as one of the most important parameters in species resilience to climate change (Thuiller, 2004; Thuiller *et al.*, 2008), terrestrial land snails comprise a very limited group in this concerning. With an average life span of 5 to 7 years, their dispersal rate is known to be around five meters per day. In addition, the topography of the central part of the island, characterized by high mountains and deep valleys, and the presence of exotic plants in the lower boundary of laurel forest restraints species dispersal to the south and between the eastern and western part of the island.

The analysis of the model results and previous knowledge about species ecology and niche requirements, suggest that important changes in species distribution may emerge from climate change scenarios.

Craspedopoma genus corresponds to the only thick operculate shell landsnails in Madeira archipelago and it is considered to be a relict fauna from the European Terciary. Four species of *Craspedopoma* are present in laurel forest, and their niche requirements are highly related to humidity and, although *Craspedopoma mucronatum* is the only widespread species in Madeira Island from this genus, all the remaining species are range-restricted, only found in localised sites.

Future projections suggest a slight expansion in *C. trochoideum* and *C. neritoide*s suitable areas; however it is important to notice that some of the new potential areas identified by our model (current and future projections) are localized in suburban areas, where disturbance factors are present and land use might not be adequate for species dispersal. In the particular case of *C. lyonnetianum*, an IUCN vulnerable species, which manly occurs in the central mountains and deep humid valleys of Funchal and São Vicente, the predicted contraction seems to be extreme, with the continuous loss of areas with suitable conditions. IUCN last assessment (made in 2011) suggests that *C. mucronatum* and *C. trochoideum* populations are stable, however, according to our model, both species may face reduction in their distribution range until the end of the century. Due to their rarity, narrow distributions, needs for highly humid habitats and potential impact of climate change, all *Craspedopoma* species are required to merit additional conservation actions and monitoring programmes, in order to ensure habitat quality and species preservation.

Associated to elevated patterns of humidity and precipitation, *Lauria fanalensis* is mainly found on ferns, moss and lichens, at intermediate elevations within Laurel forest. With little known locations in the west, is normally present in the eastern central part of the island. Current modelling predictions identified different patterns in suitable areas for *L. fanalensis*; while climate-only model suggest a reduction in future areas, the full model pointed to the potential expansion of species distribution (up to 50% in A2 scenario). Although relative humidity and precipitation are the key variables that influence species' distribution in both models, the full model also takes to account latitude and longitude, resulting in a different evolution pattern. The majority of actual species' range is currently protected by international and regional legislation; however some of the new suitable areas for this species might be over protected areas, restraining their protection.

Mostly found at high elevations in the central area of Madeira, *Leiostyla arborea* distribution is very restricted. According to the model, new suitable areas where identified for species future distribution in the surroundings of known locations; however climate-only scenario suggests a progressive reduction of suitable areas. The inclusion of vegetation and geographical variables conducts to an inverse positive future pattern; where longitude, precipitation, latitude and relative humidity are the variables that mainly influence *L. arborea* distribution. It is important to notice that *L. arborea* is longitudinally restricted, reflecting dispersal limitation mediated by the complex orography of the islands. The full model supports this assumption with the identification of the importance of spatial variables in species distribution, and the limitation of species to the central east of the island. In addition to the quality of the habitat where this species occurs, which is known to have declined in the last two decades (Seddon, 2008), the closeness to Endangered IUCN threshold, urge the need of program to monitor this species.

Restricted to the summit areas of the island, *Leiostyla colvillei*, *Leiostyla conccina*, *Leiostyla heterodon* and *Leiostyla laurinea*, are mainly found at high elevations. With only a few records known for each species, our climate model identified a wide range of suitable areas for species survival, especially in the western part of the island. These results can provide important information concerning a possible future species translocation in the future. As a result of their restrictedness, alpine species' distributions are mainly influenced by geographic variables, precipitation and presence of herbaceous and shrubby areas. According to general patterns, species are forced to move to higher elevations, reducing their distribution range and population size (Peh, 2007; Seimon *et al.*, 2007; Chen *et al.*, 2009, 2011; Velásquez-Tibatá *et al.*, 2013), matching our results, where future projections point to a drastic reduction of suitable areas for *Leiostyla colvillei*, *Leiostyla conccina* and *Leiostyla heterodon*, leading to the possible extinction of suitable areas for species survival. Sampling limitations due to the complex orography of the island and the absence of adequate future land use prediction maps, limit the study of climate change impacts on alpine species; notwithstanding urgent conservation strategies are needed in order to halt species loss.

Leiostyla cassida and *Leiostyla falknerorum* are rare species found at intermediate elevations, especially at northern locations at Funchal. These species are normally associated with humid places; some of them located in the deep valley of Ribeira de Santa Luzia and Pico do Areeiro. Listed as endangered species by IUCN (*Critically Endangered*: *L. cassida* and *Endangered*: *L. falknerorum*), both models identified new potential distribution areas in the central and southern side of the island. Future projections suggest that *L. cassida* may loose up to 60% of the current potential areas (in A2 scenario) and *L. falknerorum* might face extinction, due to the severe contraction of suitable areas. Additionally, the majority of the suitable areas suggested by the model, correspond to urbanized areas and/or places dominated by exotic vegetation. These areas, characterized by acid soils, are quite hostile for endemic land snails' survival (Teixeira, 2009), making these prediction discouraging. Last assessed in 2011 by IUCN, population trends for species are poorly known, and no recent records confirm their distribution (Seddon, 2008). The declining quality of habitats, by exotic invasion, forest fires, landslides and storms, reveal the urgent necessity of monitoring programmes for these species.

Leiostyla cheilogona, *Leiostyla irrigua*, *Leiostyla loweana* and *Leiostyla sphinctostoma* are mainly distributed in the northern, central and western side of the island, at intermediate elevations. While *L. cheilogona* is normally found amongst leaf-litter and on ferns; *L. sphinctostoma* is found on crags; and *L. loweana* and *L. irrigua* are often associated with *Marchantia* on rock crags and near waterfalls. New suitable areas for species dispersal were identified by the model. Suitable areas for *L. loweana* and *L. sphinctostoma* distribution are predicted to remain stable, showing, inclusively a slight positive trend. As a result of their wide geographical distribution, along the longitudinal gradient, these species point to an extensive heterogeneity of climatic patterns; however some of the climate suitable areas don't have the adequate habitat for species occurrence. *L. cheilogona* and *L. irrigua* exhibit negative trends for future suitable areas, and the boundaries of laurel forest until the end of the century will constitute one of the greatest limitation on species distribution. The micro-climatic association of *L. loweana* and *L. irrigua* to waterfall and "spray" areas, can represent a possible constraint in species future distribution range, as a result of artificial changes in water courses (e.g. for electricity generation) or as a consequence of precipitation and humidity variations within laurel forest.

Leiostyla vincta vincta and *L. vincta watsoniana* are normally found on the sea-cliffs of the north coast. Due to their restricted distribution, precipitation and latitude are the key variables in species distribution. Future climate scenarios suggest a negative trend for both species and, in addition to the declining quality of the habitat due to the presence of intense traffic and pollution (IUCN, 2013), urgent monitoring plans are needed for species conservation.

Listed by IUCN as Near Threatened, *Boettgeria crispa* is frequently found in the northern and central parts of the island, between 700 and 1000 meters high, and in some southern locations, always in places with high level of humidity. According to the model, new suitable areas were identified for potential species dispersal. Future projections, under climate changes, point to a decrease in suitable areas. The inclusion of vegetation classes and geographical variables seems to confine the western distribution of species, resulting in the future range decrease.

Semi-slugs from *Plutonia* genus are highly dependent of humidity and five species occur within laurel forest. *Plutonia albopalliata* (listed as *Vulnerable* by IUCN) and *Plutonia behnii* (listed as *Least Concern*) are mainly found in the central areas, at intermediate and high elevations, and also near the north coast, were laurel forest extent near the sea. According to the model, *P. albopalliata* is highly dependent of longitude, precipitation and presence of natural forest; and *P. behnii* is manly influenced by the presence of natural forest, longitude, latitude and precipitation. New suitable areas were identified for both species and future projections suggest a positive trend for *P. albopalliata* distribution and a reduction in *P. behnii* range.

Plutonia marcida, *Plutonia nitida* and *Plutonia ruivensis*, are mainly found at intermediate elevations in the central/north side of the island, in areas of big humidity. All three species seems to be confined to central and north areas; and the climatic model identified potential distribution areas for all *Plutonia* species, in the surroundings of known occurrence sites. According to the full model, due to climate change and high humidity dependency, all three species will experience a decrease in their suitable climate areas. All *Plutonia* species should be closely monitored due to the vulnerability of their habitat to climate change (Seddon, 2008) and possible changes in humidity patterns within laurel forest.

Endemic to Madeira Island *Geomitra tiarella* is normally found on the northern coastal cliffs and steep stones, and is listed as an *Endangered* species by IUCN. New potential distribution areas were identified by the model; however future projections suggest a decreasing tendency in species range, for both scenarios, possibly leading to species extinction. In addition to habitat degradation, the majority of its suitable areas is located outside protected areas, suggesting the decline on *G. tiarella*'s habitat quality and the urgent necessity of monitoring.

Actinella actinophora is found at intermediate altitudes in the central part of the island, and near the north coast, where laurel forest reaches the sea. Formerly described as common in the north intermediate elevations of Funchal (Wollaston, 1878), *Actinella arridens* is now rarely found. Although the model has suggested suitable areas in Machico, Santa Cruz and Funchal, current land-use map indicates that this area does not possess suitable habitat conditions for species survival. Consequently, even if the model suggests the expansion of *A. arridens*, a conservative approach must be performed in future conservation strategies.

Mainly restricted to less disturbed habitats in the north of the island, *Actinella fausta* also occur in the southern side, associated to deep and humid cliffs of Santa Cruz and Jardim do Mar. According to the model, new localities are available for *A. fausta* distribution, all over the island; however the predicted range of this species suggests a constriction of future suitable areas. In the other hand, *Actinella armitageana* is known to occur in the summit ridges around Pico do Areeiro and Pico Ruivo, in the central part of the island. Future climate scenarios suggest that *A. armitageana* might face challenging modifications in their distribution range. As stated before, due to laurel forest possible expansion to higher elevation (Cruz *et al.*, 2008), alpine species may experience double pressures, with the reduction of habitat and also with inter-specific pressures amongst the new arrived species (e.g. see Velásquez-Tibatá *et al.*, 2012).

With a narrower distribution than *Leptaxis membranacea*, *Leptaxis furva* is IUCN listed as a *Vulnerable* species. Assumed to live at low densities, no recent data on *L. furva* population trends are known. Potential adequate climatic niches were identified for this species and future projections suggest a positive tendency on species range. Nonetheless, the declining quality of habitat due to tourism activities and possible changes in the water management might affect species microclimate and future distribution. Also not abundant at sites, but with a wider distribution in the island, *Leptaxis membranacea* is normally found in shady valleys and ravines at intermediate and higher elevations, within Laurel forest. New distributions areas were recognized by our model; nevertheless future scenarios suggest a considerable reduction in potential suitable areas.

Without regard to our results, this analysis is not entirely conclusive, since the evaluation has only been based on species vulnerability to climate and vegetation change. It is important to notice that some of the suitable areas for species distribution are located in urban areas and in non-native forest, biasing the quantification of the extension of future range, and the real trends of each species. Moreover, most species are restricted do deep valleys, oriented in the north-south direction; being highly influenced by longitude, reflecting dispersal limitation of species, mediated by the complex orography of the islands. As a result, species future distribution will be the consequence of a broad range of variables, such as land-use, disturbance, functional traits, soil characters, geology and community dynamic parameters.

4.7. Conservation planning under climate change

The use of SDM's in modeling species future range has some limitations and the outputs should be interpreted carefully. Based on our results, whereas species with a current wider distribution may be less affected by climate change, alpine species, restricted to high mountains and, frequently, with narrow distributions, may need some additional conservation strategies.

Successful mitigation of the impact of climate change on biodiversity will depend on our protection strategies (Hannah *et al.*, 2002). A broad spectrum of measures has been suggested in order to halt species' loss, however, sometimes, current knowledge, may restraint the definition of straightforward actions. "Adaptative management" frameworks are emerging, suggesting new flexible decision-making managements tools (Kareiva *et al.*, 2008).

IUCN assessments do not contemplate climate change effects in land snails monitoring programs and conservation strategies definition (IUCN, 2013). Action and management plans should address important questions about species' adaptation and potential dispersal under future climate conditions. Urgent monitoring programs should be especially endorsed to vulnerable species and those where no population trends are known. Based in our results, we underline the need for species-specific and habitat conservation measures:

1. Monitoring programs for vulnerable species, especially for populations where future suitable climate is predicted to reduce and where population trends are unknown or unfavorable (e.g. alpine species);
2. Monitoring the physiological, behavioral and demographic species' response to climate change (thermal tolerances; phenological and behavioral adjustments, such as changes in aestivation and hibernation periods along the year and burrowing or adjustments in daily activity periods);
3. Analysis of changes in population parameters, such as abundance, fertility, mortality and quantification of specific dispersal rates (for possible species translocation; Hoegh-Guldberg *et al.*, 2008);
4. Study of species interactions, functional traits and specific habitat requirements;
5. Habitats restoring; identification of potential distribution sites; expansion of protected areas and; creation of corridors between suitable habitats (Heller and Zavaleta, 2009; Lawler, 2009).

Habitat related conservation strategies, by restoring and expansion of protected areas, have been considered one of the most effective tools to species preservation. However, the uncertain predicted distribution of species, in the future, challenge our approach and, as a result of species' shift due to their adaptation to new environmental variables, existing natural reserves and protected areas will no longer accommodate all designated species (Araújo *et al.*, 2004, 2011; Lemieux and Scott, 2005; Thuiller *et al.*, 2006; Heller and Zavaleta, 2009).

In order to improve species adaptation to rapid climatic changes, new protected areas will be necessary to enclose novel species ranges (Hannah *et al.*, 2007; Araújo, 2009; Coetzee *et al.*, 2009; Hole *et al.*, 2009). However, the inherent uncertainty of using SDMs on future climate distributions, in addition to the current economical scenario and urban development in Madeira Island, make the expansion of larger protected areas a potential unfeasible target. As a result, prioritizing investment options and management actions within nature reserves is compulsory and will affect the ability of species to adapt to climate change (Murdoch *et al.*, 2007; Carvalho, 2010).

Habitat restoration within protected areas and the improvement of connectivity amongst suitable areas might also benefit species dispersal. Due to their low dispersal ability, landscape structure and topographical features of the island, land snails may need to be assisted in this translocation.

Intensively debated amongst scientific community (McLachlan *et al.*, 2007; Mueller and Hellmann, 2008), assisted colonization has been suggested as a measure to handle climate change adaptation. Only recommended for species with low dispersal ability, highly fragmented range and in immediate risk of extinction (Hoegh-Guldberg *et al.*, 2008), assisted dispersal is particularly relevant for land snails, as long as the same biogeographic regions are safeguarded.

Climate changes are endorsed to have major ecological, social and economic implications. Emerging as one of the major threats to natural communities of the world's ecosystems, the IPCC report (2007a) states that changes in climate will not be the same across the world. The impact of these changes in fragile ecosystems might cause the loss of numerous species (Araújo *et al.*, 2004), creating new challenges for biodiversity conservation (Heller and Zavaleta, 2009), increasing the necessity of coordination among stakeholders in the region (Araújo *et al.*, 2004; Heller and Zavaleta, 2009), and mitigation and adaptation strategies to such changes has to become a priority for governments' policies.

Despite the complexity of the biological systems, the intrinsic uncertainty of species distribution models and the lack of information about land snails' functional traits, which difficult an undemanding prediction on species future trends, this analysis contributed to a pioneer study on the impacts of climate change on endemic species of Madeira Island. We believe that the inclusion of predictions of the effect of climate change on species distribution as part of IUCN assessments could contribute to species prioritizing, promoting specific management actions and maximizing future conservation investment.

5. CONCLUSION

The real impacts of climate changes on terrestrial molluscs has been neglected by IUCN assessments, and excluded from conservation efforts and biodiversity monitoring, leading to the necessity of this study, which represent the most extensive assessment on the projected impacts of climate change on species of conservation concern for Madeira archipelago.

Maximum entropy model identified potential distribution areas for thirty-one species and was able to project future suitable areas for endemic and threatened land snails' species of Madeira Island. Widely used in monitoring and conservation policies, species distribution models can be used to evaluate the potential impacts of climate change in species range size, community patterns and representation within Protected Areas. The use of SDM's in the determination of species' suitable areas has limitations and the outputs should be interpreted carefully. According to our results, species suitable areas might shift under climate and habitat change, in every analysed IPCC scenario; and, with all the inherent associated errors, our model suggests that a significant percentage of species is predicted to decrease their suitable areas by the end of the century. Nonetheless, it is important to notice that many other variables might influence land snails distribution, such as vegetation, land use, dispersion barriers and perturbation variables. The low dispersal ability, the orography of Madeira's landscape, the presence of exotic vegetation and disturbed areas, and also internal population dynamics will certainly limit terrestrial mollusc turnover to favourable areas.

The successful mitigation of the impact of climate change on biodiversity depends on a very specific set of tools related to the analysis of the distribution of species. Many measures have been suggested in order to identify and understand the underlying causes of climate impacts, and its influence on species trends. Predictive models of species distribution coupled with the use of GIS and climate change scenarios have become crucial to identify threats and determine biodiversity vulnerability, resulting in an "Adaptative management" framework, contributing to species conservation and definition of management strategies.

Although IUCN assessments do not contemplate climate change effects in land snails monitoring programs and conservation strategies definition, action and management plans should address important questions about species' adaptation and potential dispersal under future climate conditions. Urgent monitoring programs should be especially endorsed to vulnerable species and those where no population trends are known.

Notwithstanding the complexity of the ecosystems, the fundamental uncertainty of species distribution models and the lack of information about land snails' functional traits, which difficult an undemanding prediction on species future trends, this analysis contributed to a pioneer study on the impacts of climate change on endemic species of Madeira Island. We believe that the inclusion of predictions of the effect of climate change on species distribution as part of IUCN assessments could contribute to species prioritizing, promoting specific management actions and maximizing future conservation investment.

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ANNEX 1

List of target species and environmental data used in the model.

ID	Genus	Species	Order	Family	Authority	Red List status	Red List criteria version	Year assessed	Population trend
1	*Actinella*	*actinophora*	Stylommatophora	Hygromiidae	(R.T. Lowe, 1831)	VU	3.1	2011	unknown
2	*Actinella*	*armitageana*	Stylommatophora	Hygromiidae	(Lowe, 1852)	VU	3.1	2011	unknown
3	*Actinella*	*arridens*	Stylommatophora	Hygromiidae	(R.T. Lowe, 1831)	CR	3.1	2011	unknown
4	*Actinella*	*carinofausta*	Stylommatophora	Hygromiidae	Waldén, 1983	EN	2.3	2011	unknown
5	*Actinella*	*fausta*	Stylommatophora	Hygromiidae	(Lowe, 1831)	LC	3.1	2011	unknown
6	*Boettgeria*	*crispa*	Stylommatophora	Clausiliidae	(Lowe, 1831)	NT	3.1	2011	stable
7	*Caseolus*	*calvus*	Stylommatophora	Hygromiidae	(Lowe, 1831)	EN	3.1	2011	unknown
8	*Craspedopoma*	*lyonnetianum*	Architaenioglossa	Craspedopomatidae	Lowe, 1852	VU	3.1	2011	unknown
9	*Craspedopoma*	*mucronatum*	Architaenioglossa	Craspedopomatidae	(Menke, 1830)	LC	3.1	2011	stable
10	*Craspedopoma*	*neritoides*	Architaenioglossa	Craspedopomatidae	(Lowe, 1860)	LC	3.1	2011	unknown
11	*Craspedopoma*	*trochoideum*	Architaenioglossa	Craspedopomatidae	Lowe, 1860	LC	3.1	2011	stable
12	*Geomitra*	*delphinuloides*	Stylommatophora	Hygromiidae	(R. T. Lowe, 1860)	CR	3.1	2011	unknown
13	*Geomitra*	*tiarella*	Stylommatophora	Hygromiidae	Webb & Berthelot, 1833	EN	3.1	2011	unknown
14	*Hemilauria*	*limnaeana*	Stylommatophora	Lauriidae	(Lowe, 1852)	LC	3.1	2011	stable
15	*Lauria*	*fanalensis*	Stylommatophora	Lauriidae	(Lowe, 1852)	LC	3.1	2011	stable
16	*Leiostyla*	*arborea*	Stylommatophora	Lauriidae	(Lowe, 1855)	VU	3.1	2011	unknown
17	*Leiostyla*	*cassida*	Stylommatophora	Lauriidae	(Lowe, 1831)	CR	3.1	2011	decreasing
18	*Leiostyla*	*cassidula*	Stylommatophora	Lauriidae	(R.T. Lowe, 1852)	CR	2.3	2011	unknown
19	*Leiostyla*	*cheilogona*	Stylommatophora	Lauriidae	Lowe, 1864	LC	3.1	2011	stable
20	*Leiostyla*	*colvillei*	Stylommatophora	Lauriidae	Seddon & Killeen, 1996	VU	3.1	2011	unknown

21	*Leiostyla*	*concinna*	Stylommatophora	Lauriidae	(R.T. Lowe, 1852)	EN	3.1	2011	unknown
22	*Leiostyla*	*falknerorum*	Stylommatophora	Lauriidae	Bank, Groh & Ripken, 2002	EN	3.1	2011	unknown
23	*Leiostyla*	*heterodon*	Stylommatophora	Lauriidae	(Pilsbry, 1923)	VU	3.1	2011	unknown
24	*Leiostyla*	*irrigua*	Stylommatophora	Lauriidae	(Lowe, 1852)	LC	3.1	2011	stable
25	*Leiostyla*	*laurinea*	Stylommatophora	Lauriidae	(R.T. Lowe, 1852)	VU	3.1	2010	unknown
26	*Leiostyla*	*loweana*	Stylommatophora	Lauriidae	(Wollaston, 1878)	LC	3.1	2011	stable
27	*Leiostyla*	*sphinctostoma*	Stylommatophora	Lauriidae	(Lowe, 1831)	LC	3.1	2011	stable
28	*Leiostyla*	*vincta vincta*	Stylommatophora	Lauriidae	(Lowe, 1852)	LC	3.1	2011	stable
29	*Leiostyla*	*vincta watsoniana*	Stylommatophora	Lauriidae	(Pilsbry, 1923)				
30	*Leptaxis*	*furva*	Stylommatophora	Hygromiidae	(R.T. Lowe, 1831)	VU	3.1	2011	unknown
31	*Leptaxis*	*membranacea*	Stylommatophora	Hygromiidae	(R.T. Lowe, 1852)	LC	3.1	2011	unknown
32	*Plutonia*	*albopalliata*	Stylommatophora	Vitrinidae	(Groh & Hemmen, 1986)	VU	3.1	2011	unknown
33	*Plutonia*	*behnii*	Stylommatophora	Vitrinidae	(R.T. Lowe, 1852)	LC	3.1	2011	stable
34	*Plutonia*	*marcida*	Stylommatophora	Vitrinidae	(A.A. Gould, 1847)	LC	3.1	2011	stable
35	*Plutonia*	*nitida*	Stylommatophora	Vitrinidae	(A.A. Gould, 1847)	LC	3.1	2011	stable
36	*Plutonia*	*ruivensis*	Stylommatophora	Vitrinidae	(A.A. Gould, 1847)	LC	3.1	2011	stable

Table 1: Land snails’ nomenclature, IUCN conservation status and population trends.

Variable	**Description**	**Type**	**Source**
TMEAN	Annual mean temperature	continuous	CLIMAAT
TMAX	Annual maximum temperature	continuous	CLIMAAT
TMIN	Annual minimum temperature	continuous	CLIMAAT
PMEAN	Annual mean precipitation	continuous	CLIMAAT
PMAX	Annual maximum precipitation	continuous	CLIMAAT
PMIN	Annual minimum precipitation	continuous	CLIMAAT
RHMEAN	Annual mean relative humidity	continuous	CLIMAAT
RHMAX	Annual maximum relative humidity	continuous	CLIMAAT
RHMIN	Annual minimum relative humidity	continuous	CLIMAAT
ALT	Altimetry	continuous	APA[1]
SLO	Slope	continuous	APA[1]
SOIL	Soil type	categorical	SRA[2]
GEOL	Geology	categorical	SRA[2]
LAT	Latitude	continuous	APA[1]
LONG	Longitude	continuous	APA[1]
NFOR	Natural forest	categorical	COSRAM2007[3]
NSRHU	Natural shrub areas	categorical	COSRAM2007[3]
NHERB	Natural herbaceous vegetation	categorical	COSRAM2007[3]

Table 2: Environmental variables used in the model ([1]APA: Agência Portuguesa de Ambiente; [2]SRA: Secretaria Regional do Ambiente e dos Recursos Naturais; [3]COSRAM2007: Carta de Ocupação de Solo da Região Autónoma da Madeira).

ANNEX 2

Scripts used to perform geoprocessing operations and *Map algebra* expressions to estimate community patterns.

```
import arcpy

arcpy.env.workspace ='c:\progsig'

especie = arcpy.GetParameterAsText(0)
costa = arcpy.GetParameterAsText(1)
output_clipcentr = arcpy.GetParameterAsText(2)

arcpy.MakeFeatureLayer_management(especie, 'temp_especie')
```

Figure 1: Python scripting for *Clipping* and *Centroid definition*.

```
import arcpy

arcpy.env.workspace = "C:/progsig/resultados_clipcentr"

try:

    inFeatures = arcpy.GetParameterAsText(0)
    fieldName1 = "xCentroid"
    fieldName2 = "yCentroid"
    fieldPrecision = 16
    fieldScale = 8

    expression1 = "float(!SHAPE.CENTROID!.split()[0])"
```

Figure 2: Python scripting for *Centroids coordinates' attribution*.

```
import arcgisscripting, os


gp = arcgisscripting.create()


InAsciiFile = None

inDir = r"C:/CChange/species_thr/thr_in/thr_b2_70"

OutRaster = "C:/CChange/species_thr/thr_out/thr_b2_70"
```

Figure 3: Python scripting for converting multiple ASCII to Raster.

```
import arcpy, os

from arcpy import env

from arcpy.sa import *


env.workspace = "C:/CChange/species_thr/thr_out/thr_b2_70"


inRaster01 = "p_rui0"

inRaster02 = "p_rui1"

inRaster03 = "p_rui2"

inRaster04 = "p_rui3"
```

Figure 4: Python scripting to calculate the sum of the ten replicates for each species.

```
import arcpy

from arcpy import env

from arcpy.sa import *

import os


env.workspace = "C:/CChange/species_thr/thr_out/total_thr_ct"


rasterList = arcpy.ListRasters("*", "All")


rasterList.sort()
```

Figure 5: Python scripting for reclassifying several Rasters.

Beta diversity indexes	**Expression**
Beta Diversity β_{cc}	(("B-Loss Maps\a2040-ct_loss" + "C-Gain Maps\a2040-ct_gain")*100) / ("A-Maintenance Maps\a2040-ct_mnt" + "B-Loss Maps\a2040-ct_loss" + "C-Gain Maps\a2040-ct_gain")
Species Replacement β_{-3}	2 * (CellStatistics(["B-Loss Maps\a2040-ct_loss","C-Gain Maps\a2040-ct_gain"], "MINIMUM") * 100 / ("A-Maintenance Maps\a2040-ct_mnt" + "B-Loss Maps\a2040-ct_loss" + "C-Gain Maps\a2040-ct_gain"))
Species richness differences β_{rich}	(Abs("B-Loss Maps\a2040-ct_loss" - "C-Gain Maps\a2040-ct_gain") * 100) / ("A-Maintenance Maps\a2040-ct_mnt" + "B-Loss Maps\a2040-ct_loss" + "C-Gain Maps\a2040-ct_gain")

Table 1: *Map algebra* expressions to estimate *Beta diversity*, *Species replacement* and *Species richness differences* (example for A2 scenario, differences between current and 2040-69 period).

ANNEX 3

Predictive distribution maps for habitat modelling.

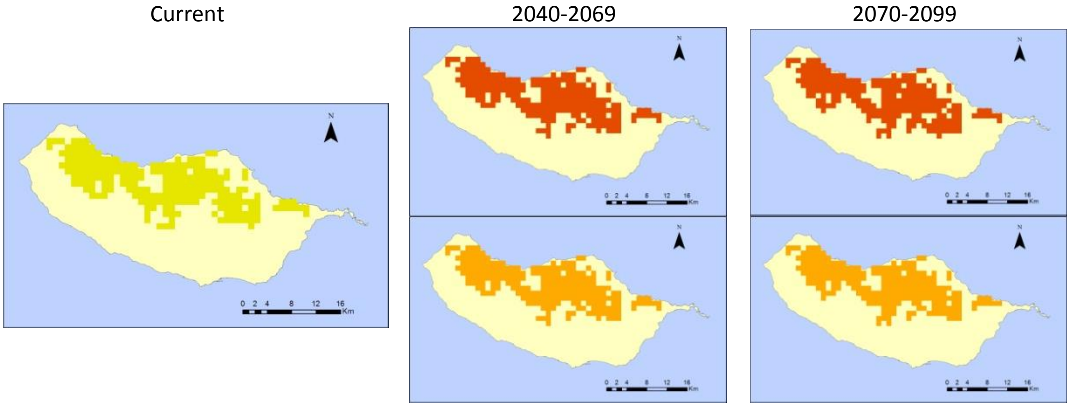

Figure 1: Predictive distribution maps for natural forest areas. On the left side, green patches correspond to the predicted distribution in the present. Following columns present the modelled distribution of vegetation under future climatic and habitat change scenarios (red for A2 and orange for B2).

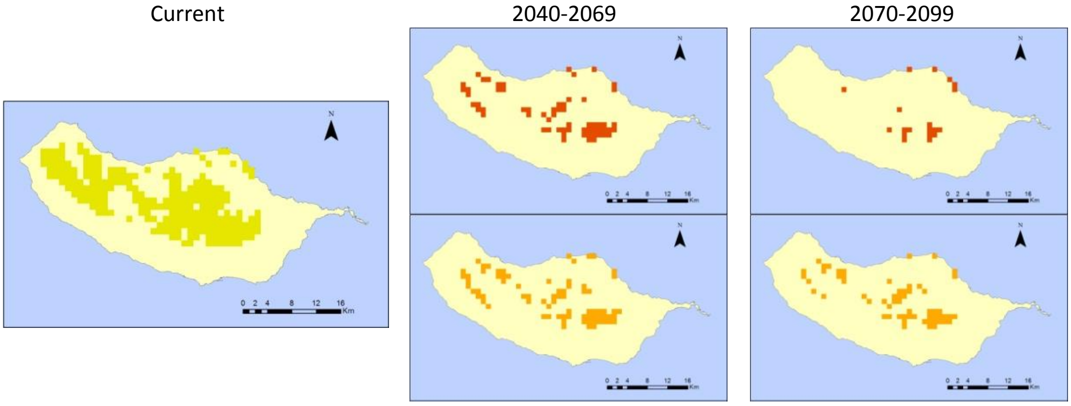

Figure 2: Predictive distribution maps for natural shrub areas. On the first row, green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of vegetation under future climatic and habitat change scenarios (red for A2 and orange for B2).

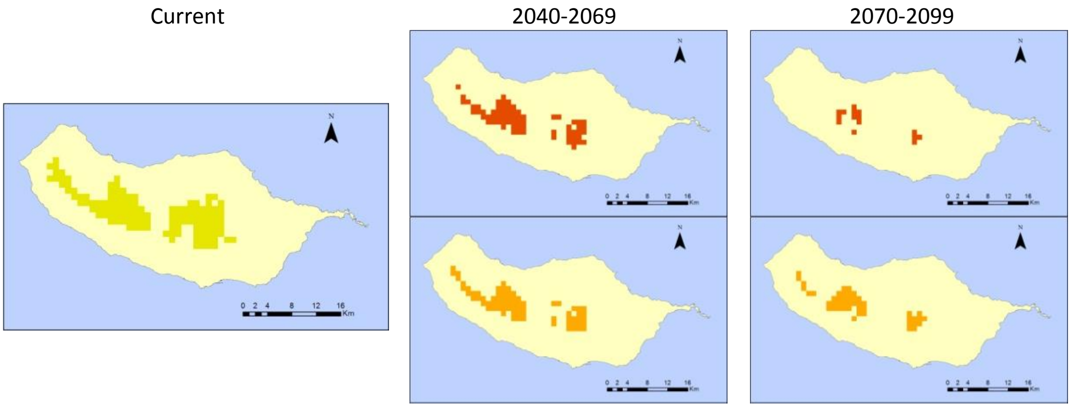

Figure 3: Predictive distribution maps for natural herbaceous vegetation. On the first row, green patches correspond to the predicted distribution in the present. Following rows present the modelled distribution of vegetation under future climatic and habitat change scenarios (red for A2 and orange for B2).

ANNEX 4

Resume of MaxEnt results: AUC values and jacknife analysis.

Species	n	**Dataset 1** (climate variables)		**Dataset 2** (all variables)	
		AUC	**STD AUC**	**AUC**	**STD AUC**
Actinella actinophora	51	0.8538	0.0648	0.9373	0.0580
Actinella armitageana	34	0.9700	0.0200	0.9893	0.0053
Actinella arridens	24	0.8206	0.1153	0.9504	0.0634
Actinella fausta	82	0.7413	0.0800	0.8286	0.0645
Boettgeria crispa	126	0.8564	0.0378	0.9363	0.0288
Craspedopoma lyonnetianum	31	0.7836	0.0976	0.9151	0.0662
Craspedopoma mucronatum	339	0.7127	0.0393	0.8486	0.0302
Craspedopoma neritoides	99	0.7776	0.0588	0.9095	0.0358
Craspedopoma trochoideum	98	0.8756	0.0422	0.9374	0.0277
Geomitra tiarella	20	0.9620	0.0152	0.9905	-0.2926
Leiostyla arborea	31	0.8863	0.0654	0.9736	0.0312
Leiostyla cassida	23	0.8080	0.0865	0.9790	0.0089
Leiostyla cheilogona	94	0.8279	0.0523	0.9409	0.0290
Leiostyla colvillei	12	0.8959	-0.7968	0.9932	-0.7995
Leiostyla concinna	26	0.9477	0.0326	0.9861	0.0100
Leiostyla falknerorum	11	0.9765	-0.8996	0.9865	-0.8932
Leiostyla heterodon	17	0.9950	-0.2983	0.9957	-0.2982

Leiostyla irrigua	75	0.8216	0.0773	0.9133	0.0458
Leiostyla laurinea	41	0.8280	0.0628	0.9691	0.0242
Leiostyla loweana	114	0.7861	0.0530	0.9252	0.0289
Leiostyla sphinctostoma	146	0.7557	0.0613	0.8695	0.0508
Leiostyla vincta vincta	33	0.9514	0.0266	0.9826	0.0115
Leiostyla vincta watsoniana	16	0.9328	-0.3876	0.9553	-0.3835
Lauria fanalensis	43	0.9164	0.0366	0.9453	0.0296
Leptaxis furva	36	0.8851	0.0563	0.9512	0.0350
Leptaxis membranacea	238	0.7625	0.0389	0.8734	0.0341
Plutonia albopalliata	69	0.8003	0.0715	0.9214	0.0408
Plutonia behnii	99	0.8498	0.0467	0.9456	0.0273
Plutonia marcida	222	0.7850	0.0329	0.8729	0.0309
Plutonia nitida	120	0.8051	0.0525	0.8955	0.0407
Plutonia ruivensis	245	0.7590	0.0365	0.8511	0.0364

Table 1: Land snails' species list, number of records of each species within Madeira Island, and AUC values obtained for training data, under both models.

Species	n	AUC	TMAX	PMIN	RHMIN	NFOR	NSRHU	NHERB	LAT	LONG
A. actinophora	51	0.8538	28.2312	14.9646	56.8042	-	-	-	-	-
A. armitageana	34	0.9700	79.8598	11.2950	8.8453	-	-	-	-	-
A. arridens	24	0.8206	27.2056	47.7640	25.0305	-	-	-	-	-
A. fausta	82	0.7413	9.8344	4.9653	85.2003	-	-	-	-	-
B. crispa	126	0.8564	82.3520	6.2060	11.4419	-	-	-	-	-
C. lyonnetianum	31	0.7836	62.2106	28.214	9.5754	-	-	-	-	-
C. mucronatum	339	0.7127	10.5457	15.6593	73.7950	-	-	-	-	-
C. neritoides	99	0.7776	67.7017	6.9266	25.3717	-	-	-	-	-
C. trochoideum	98	0.8756	20.6754	13.2689	66.0556	-	-	-	-	-
G. tiarella	20	0.9620	0.1540	67.2995	32.5464	-	-	-	-	-
L. arborea	31	0.8863	0.7209	81.2048	18.0743	-	-	-	-	-
L. cassida	23	0.8080	54.8486	17.6353	27.5160	-	-	-	-	-
L. cheilogona	94	0.8279	35.427	11.5749	52.9980	-	-	-	-	-
L. colvillei	12	0.8959	3.9660	95.0172	1.0168	-	-	-	-	-
L. concinna	26	0.9477	25.2297	65.7947	8.9756	-	-	-	-	-
L. falknerorum	11	0.9765	16.4949	45.8064	37.6987	-	-	-	-	-
L. heterodon	17	0.9950	54.7122	36.8196	8.4682	-	-	-	-	-
L. irrigua	75	0.8216	41.3472	35.0958	23.5570	-	-	-	-	-
L. laurinea	41	0.8280	73.6526	23.2041	3.1433	-	-	-	-	-
L. loweana	114	0.7861	5.8192	9.2530	84.9278	-	-	-	-	-
L. sphinctostoma	146	0.7557	10.9658	25.1226	63.9115	-	-	-	-	-

L. vincta vincta	33	0.9514	2.4131	55.9485	41.6384	-	-	-	-	-
L. vincta watsoniana	16	0.9328	6.2358	42.8473	50.9169	-	-	-	-	-
L. fanalensis	43	0.9164	6.2037	23.4069	70.3894	-	-	-	-	-
L. furva	36	0.8851	0.6952	85.2678	14.0370	-	-	-	-	-
L. membranacea	238	0.7625	37.2482	13.4882	49.2636	-	-	-	-	-
P. albopalliata	69	0.8003	14.2282	75.0758	10.6960	-	-	-	-	-
P. behnii	99	0.8498	27.3831	46.8114	25.8056	-	-	-	-	-
P. marcida	222	0.7850	28.7824	7.7342	63.4834	-	-	-	-	-
P. nitida	120	0.8051	51.8129	24.7258	23.4613	-	-	-	-	-
P. ruivensis	245	0.7590	44.2001	13.5513	42.2486	-	-	-	-	-

Table 2: Species list, number of occurrences (n), area under the curve (AUC) and contribution of each variable to the model in current scenario (climate change variables only): TMAX – maximum temperature; PMIN – minimum precipitation; RHMIN – minimum relative humidity; NFOR – natural forest; NSHRU – natural shrub; NHERB – herbaceous vegetation; LAT - latitude; and LONG - longitude.

Species	n	AUC	TMAX	PMIN	RHMIN	NFOR	NSRHU	NHERB	LAT	LONG
A. actinophora	51	0.9373	6.1377	5.2986	7.8028	22.0739	0.1117	8.1478	16.4044	34.0231
A. armitageana	34	0.9893	17.7106	4.3108	2.6279	0.0213	23.4856	24.1829	3.9630	23.6980
A. arridens	24	0.9504	9.4184	14.6171	17.5182	12.2206	3.4663	0.1713	8.8962	33.6919
A. fausta	82	0.8286	4.9143	4.9771	27.8959	0.0007	1.0494	11.5071	31.2873	18.3682
B. crispa	126	0.9363	30.1699	1.3731	0.7624	25.1226	0.4922	0.0465	7.2753	34.7580
C. lyonnetianum	31	0.9151	3.2729	2.2876	1.6874	13.7267	9.1839	21.7892	11.3348	36.7175
C. mucronatum	339	0.8486	0.7139	3.9353	0.9603	35.4967	0.0170	0.0026	17.6497	41.2244
C. neritoides	99	0.9095	9.6608	2.6515	1.0891	46.3777	1.1692	0.0613	10.4264	28.5641
C. trochoideum	98	0.9374	2.8182	3.9720	1.4708	53.4706	4.8241	2.0587	22.2091	9.1764
G. tiarella	20	0.9905	0.0785	51.6004	1.2428	15.8247	0.1121	0	23.0261	8.1155
L. arborea	31	0.9736	0.4783	33.0613	7.5380	4.5537	2.3211	2.4059	11.3808	38.2610
L. cassida	23	0.9790	0.3216	3.5266	1.2005	12.2359	2.0815	28.6918	13.1049	38.8372
L. cheilogona	94	0.9409	12.6193	0.9001	5.7604	23.7626	0.7272	0.9312	19.3271	35.9722
L. colvillei	12	0.9932	0	1.9662	0.0109	6.5000	0.1570	58.3934	0.2301	32.7424
L. concinna	26	0.9861	3.7066	22.2910	3.4139	0.5494	32.6498	3.0977	12.4342	21.8574
L. falknerorum	11	0.9865	3.4122	16.6298	15.8151	6.8616	21.2156	5.8489	23.2127	7.0042
L. heterodon	17	0.9957	21.4357	17.8999	3.3595	2.3492	10.0572	30.2999	0.7017	13.8969
L. irrigua	75	0.9133	3.8662	15.5064	14.0925	23.3660	4.2204	0.0342	3.2114	35.7031
L. laurinea	41	0.9691	4.9853	8.4466	1.0974	32.8400	4.6473	0.0113	22.7667	25.2055
L. loweana	114	0.9252	0.7369	1.9491	5.7700	11.5868	0.0100	0.4612	44.9309	34.5551
L. sphinctostoma	146	0.8695	4.9464	8.6323	22.2383	5.4733	0.4925	2.2084	14.6986	41.3101

L. vincta vincta	33	0.9826	1.0931	39.0465	4.3213	18.1634	0.6060	0	25.9994	10.7704
L. vincta watsoniana	16	0.9553	0.0037	30.8661	11.0919	0.1767	0.3843	0	48.8678	8.6094
L. fanalensis	43	0.9453	1.2338	15.3397	54.1377	2.3324	3.3587	0.2657	13.1118	10.2202
L. furva	36	0.9512	0.0764	26.1611	2.5786	30.8702	1.2372	16.0207	9.0305	14.0254
L. membranacea	238	0.8734	12.2468	4.1128	0.3559	30.6886	0.0311	0.0589	21.4242	31.0817
P. albopalliata	69	0.9214	0.1925	20.5738	1.4216	19.2293	3.8660	8.5885	16.4655	29.6628
P. behnii	99	0.9456	0.6238	15.4610	1.4064	33.4139	0.1145	0.4832	17.6544	30.8429
P. marcida	222	0.8729	17.4370	2.2269	3.9074	11.9069	0.1052	0.1727	37.8374	26.4066
P. nitida	120	0.8955	25.8282	10.5980	4.3559	0.7025	2.3183	2.7109	24.9155	28.5707
P. ruivensis	245	0.8511	16.2644	5.8373	3.5840	23.3959	0.5172	0.5549	21.9883	27.8580

Table 3: Species list, number of occurrences (n), area under the curve (AUC) and contribution of each variable to the model in current scenario (climate change and habitat variables): TMAX – maximum temperature; PMIN – minimum precipitation; RHMIN – minimum relative humidity; NFOR – natural forest; NSHRU – natural shrub; NHERB – herbaceous vegetation; LAT - latitude; and LONG - longitude.