Chapter 12
Climate Change and Biodiversity in the Atlantic Forest: Best Climatic Models, Predicted Changes and Impacts, and Adaptation Options

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12.1 Current and Future Climate

The Atlantic Forest, with its large latitudinal and altitudinal range, is under different climatic regimes. The current spatial distribution of the Brazilian Atlantic Forest can be linked to several meteorological processes currently at play in the region. These processes have important influences on the observed temperature and rainfall, which in turn drive the environmental conditions needed for the occurrence of the Atlantic Forest vegetation (Salazar et al. 2007; Carnaval et al. 2009; Colombo and Joly 2010). One of these processes is the occurrence of cold fronts (Cavalcanti and Kousky 2009), which are characterized by relatively colder and denser air masses moving from the polar region interacting with moist and hot air, causing a substantial drop in temperature and an increase in precipitation. Cold fronts are most common in the central and southern portions of the Atlantic Forest (latitudes <15° S) (Cavalcanti and Kousky 2009), where their impacts are most relevant. Another process linked to the range of precipitation and temperature observed in a large portion of the Atlantic Forest is a large-scale atmospheric circulation pattern known as the South Atlantic Convergence Zone. This meteorological system is characterized

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by an elongated northwest-southeast region, from the Amazon to southeastern Brazil, where convergent winds, clouds, and substantial precipitation are observed during the summer (Carvalho and Jones 2009). In the portions of the Atlantic Forest located in the northeast of Brazil, the South Atlantic portion of the Intertropical Convergence Zone plays an essential role on the precipitation (Melo et al. 2009). This system is also characterized by the convergence of surface air, clouds, and precipitation and happens typically during March and April.

An additional, essential feature that interacts with the atmospheric patterns discussed above is topography, which in the Atlantic Forest is particularly relevant in the Serra do Mar mountain range (see Carlucci et al. 2021 Chap. 5). Mountain ridges may lift air masses, enhancing cloud and rain formation. Also, as the temperature usually decreases with altitude in the troposphere, locations at sea level or mountaintops will usually present different species.

As we see, atmosphere, ocean, and topography have a great influence on climate and vegetation cover. Indeed, these are essential components of the general circulation models (GCMs) used both for meteorological and climate change predictions. The GCMs used to project future changes in climate due to ongoing climate change incorporate both the natural and anthropogenic dynamics in the main components of the Earth system, usually the atmosphere and oceans, but also the cryosphere and land use/land cover, among others. They are developed by dozens of research institutions worldwide, using standard basic protocols established by the Coupled Model Intercomparison Project and adopted by the Intergovernmental Panel on Climate Change (IPCC) (Taylor et al. 2012). The projections are made under different scenarios of future greenhouse gas concentrations in the atmosphere, called representative concentration pathways (RCPs). There are four such scenarios, ranging from the most optimistic RCP 2.6, where emissions are reduced by about 90% in 2100 compared with the present and a projected average global increase of 1.5 °C by the end of the century, to the most pessimistic RCP 8.5, where greenhouse gas emissions continue mostly untapped, and an average global increase of 4.0 °C is projected by the end of the century (Van Vuuren et al. 2011; Knutti and Sedláček 2012; IPCC 2013).

The Brazilian National Institute for Space Research (INPE) has developed a GCM, the Brazilian Earth System Model (BESM), with the objective of assembling the scientific expertise capable of developing and maintaining a state-of-the-art Earth system model and the aim of participating in the Coupled Model Intercomparison Project Phase 6 (Veiga et al. 2019). On top of global climate models, which have a global extent, there are regional climate models (RCMs), which cover a specific region of the globe, such as a country or a continent, and typically have a higher spatial resolution and a better performance within the region of interest. RCMs need to be nested within a GCM that provides the input data for the external geographic boundary of the RCM. The Brazilian National Institute for Space Research has also developed an RCM for South America, the CPTEC Eta model, with versions nested within the HadGem (UK), MIROC (Japan), and BESM (Brazil) (Chou et al. 2014).

Projected changes in climate can differ widely among GCMs, and different GCMs are known to perform better in specific regions of the globe (e.g., Cai et al. 2009; Yin et al. 2013). Therefore, studies that aim at projecting the future impacts of ongoing climate change on biodiversity, such as species distribution models, should use GCMs that show a good performance in the region of study. This information, however, is not readily available for most regions, especially in the Tropics, and definitely not for the Atlantic Forest. To fill this gap, we provide here an evaluation of the performance of different GCMs over the Atlantic Forest.

We evaluated the performance of 48 GCMs from CMIP5 Phase 5 (used in the last IPCC Assessment Report; Taylor et al. 2012) using Taylor Diagrams (Taylor 2001). Simulations are available at https://esgfnode.llnl.gov/search/esgf-llnl/. The Taylor diagram provides a graphical framework that allows a suite of variables from a variety of models to be compared to reference data. We compared the modeled (GCM) historical data (1850–2005) with the observed historical data (1979–2005) derived from TRMM (Tropical Rainfall Measuring Mission) and ERA-Interim for precipitation and air surface temperature, respectively (Dee et al. 2011; Huffman et al. 2014). Taylor diagrams quantify the spatial similarity of each GCM with respect to observations in terms of the spatial correlation coefficient, the root-mean-square error (RMSE), and the ratio of their variances (Taylor 2001).

We worked under the assumption that, if the models realistically simulate the present climate, they will be able to provide more confident projections of future states. Therefore, after identifying the set of models with the best simulation of seasonal patterns for precipitation and air surface temperature according to the Taylor diagrams, we analyzed their projections for the twenty-first century under the RCP 8.5 scenario. We evaluated the projected change by the end of the twenty-first century (2071–2100) using the 1971–2000 period as the baseline.

The results point to eight GCMs as the best models for the Atlantic Forest (Fig. 12.1, Table 12.1). The data for these GCMs, downscaled and calibrated (bias-corrected), is freely available for download in standard GIS format in the WorldClim Global Climate data portal (https://www.worldclim.org/CMIP5v1). The projected change under the RCP 8.5 scenario showed, on average, the regional increase in temperature between ca. 4.8 °C and 5.6 °C, while precipitation did not show a clear future trend (Fig. 12.2). The lack of trend for precipitation for the Atlantic Forest as a whole is likely because it lies in a region that shows different projections, with an expected decrease in precipitation in its northern portion but an increase in its southern and southeastern portion (Fig. 12.3). This effect is why the Atlantic Forest is often separated into two portions (north and south) in studies related to climate change (e.g., PBMC 2014).

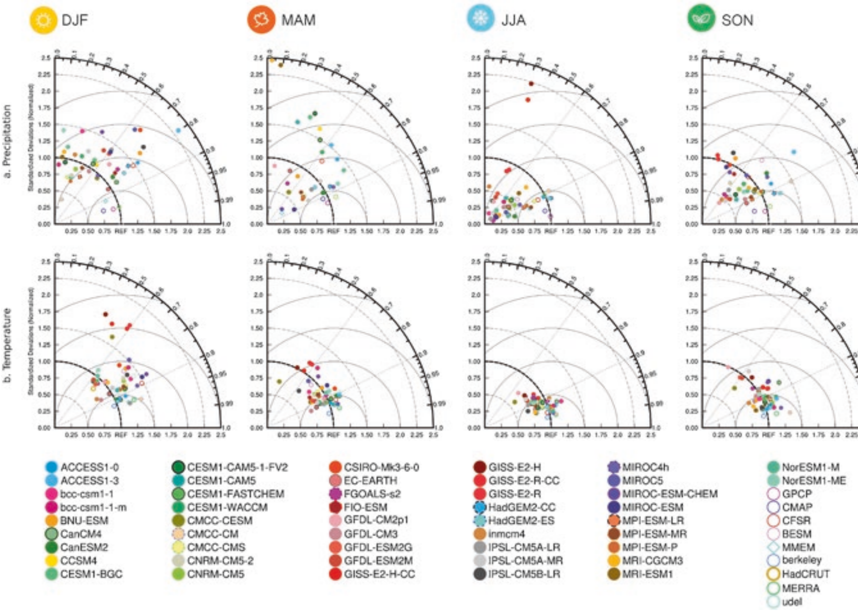

Fig. 12.1 Taylor diagrams for seasonal simulations of precipitation (top) and air surface temperature (bottom). GCMs are shown by full circles, while observational datasets and BESM (Brazilian Earth System Model) are shown with open circles. For each data point, three statistics are plotted: the Pearson correlation coefficient is shown in the azimuthal angle (dashed straight lines), the root-mean error in GCM is proportional to the distance from the point on the x-axis identified as "REF" (bold black dashed line contours), and the ratio of variance of GCM is proportional to the radial distance from the origin (black solid line contours). The distance between each data point and "REF" is a measure of how realistically each GCM reproduces the observational datasets (see Taylor 2001 for further details). DJF, December, January, February; MAM, March, April, May; JJA, June, July, August; SON, September, October, November

Table 12.1 Subset of best global climate models for the Atlantic Forest according to Taylor diagrams. Model types: Atmosphere-Ocean General Circulation Models (AOGCMs) and Earth System Models (ESM; includes land use/land cover and the biosphere)

Model name	Institution	Type
ACCESS1.0	CSIRO and Bureau of Meteorology (BOM), Australia	AOGCM
CanCM4	Canadian Centre for Climate Modelling and Analysis, Canada	AOGCM
CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada	ESM
CMCC-CM	Centro euro-Mediterraneo per I CambiamentiClimatici, Italy	AOGCM
HadGEM2-CC	Met Office Hadley Centre, United Kingdom	ESM
HadGEM2-ES	Met Office Hadley Centre, United Kingdom	ESM
MIROC4h	Japan Agency for Marine-Earth Science and Technology, atmosphere and ocean research institute, and national institute for environmental studies, Japan	ESM
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany	ESM

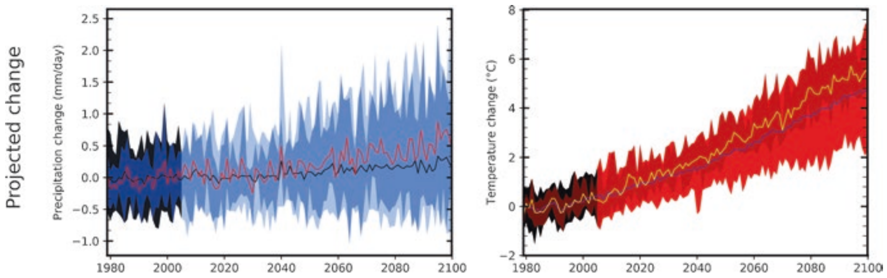

Fig. 12.2 Projected change of precipitation (left) and air surface temperature (right) over the Atlantic Forest by the end of the twenty-first century. Changes were calculated as the difference between the mean RCP 8.5 projection by the end of the century (2071–2100) and the mean historical simulation (1971–2000), using only the best global climate models for the Atlantic Forest according to the Taylor diagrams

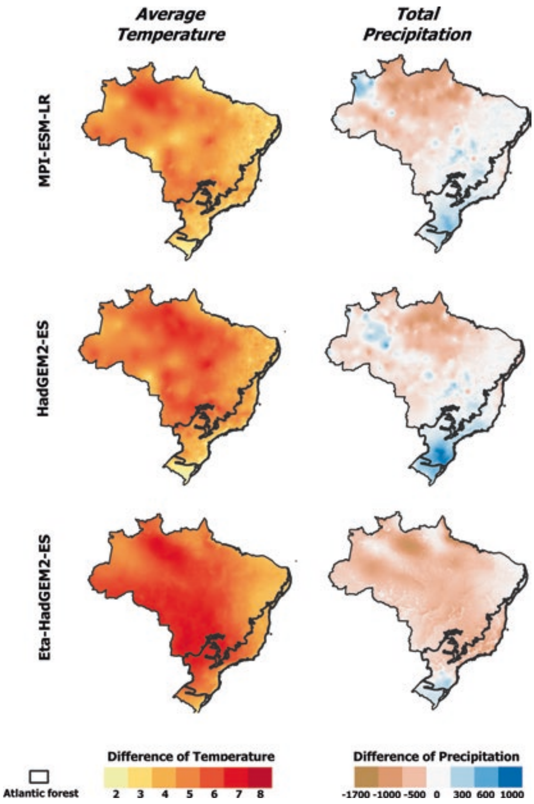

Fig. 12.3 Projected change in mean temperature (left) and total precipitation (right) in Brazil. Change was calculated for two global climate models with good performance over the Atlantic Forest (MPI-ESM-LR and HadGEM2-ES) using data from the WorldClim Global Climate database and a South America regional climate model (ETA-HadGEM ES)

12.2 Impacts of Climate Change on Biodiversity

No studies to date have shown observed impacts of ongoing climate on biodiversity in the Atlantic Forest, but there is a growing number of studies that project future impacts. A global-scale study that combined vulnerability associated with future climate change hazard, future suitability to the invasion by invasive alien species, and current land use changes placed the Atlantic forest among the top three most vulnerable biodiversity hotspots in the world (Bellard et al. 2014).

The bulk of the studies on project impacts of climate change the Atlantic First biodiversity rely on species distribution models under future climatic conditions, which are increasingly being combined with land use change. The Atlantic Forest, together with Cerrado, is possibly the hotspot with the highest number of such studies in South America (Bustamante et al. 2019). There is a clear taxonomic bias in studies toward terrestrial vertebrates, especially not only towards birds and amphibians (e.g., Marini et al. 2010; Souza et al. 2011; Loyola et al. 2014; Lemes and Loyola 2013; Lemes et al. 2014; Hoffmann et al. 2015; Vasconcelos and Nascimento 2016; Vale et al. 2018; Vasconcelos et al. 2018) but also mammals (e.g., Meyer et al. 2014; Gouveia et al. 2016; Lima et al. 2019) and reptiles (e.g., Lourenço-de-Moraes et al. 2019), and also some studies on invertebrates, especially insects (Ferro et al. 2014; Gianinni et al. 2012, 2015; Beltramino et al. 2015; Faleiro et al. 2018; Françoso et al. 2019) and plants (Colombo and Joly 2010; Cupertino-Eisenlohr et al. 2017). The studies typically predict a reduction of the distribution or climatic suitability in the future for the vast majority of the species and expansion for few. An exception is Zwiener et al. (2017a), who predicted a general increase in local richness of woody plants, but mainly for the generalist and disturbance-tolerant species, and a decrease in beta diversity and biotic homogenization at large scales. Few studies consider biological interactions under climate change (e.g., see Vasconcelos et al. 2017 for mutualism and Braz et al. 2019 for competition) and invasive species (e.g., Nori et al. 2011; Assunção et al. 2018). Many studies also predict a southward range shifts (e.g., Colombo and Joly 2010; Ferro et al. 2014; Lemes et al. 2014; Beltramino et al. 2015; Hoffmann et al. 2015; Vale et al. 2018; Silva et al. 2019), which might be a compensation for increased temperatures, and is congruent with a projected southward expansion of the Atlantic Forest vegetation (Salazar et al. 2007). The result is a predicted reduction in species richness and an increase in turnover, in general (which might be clade-specific for amphibians at least; Loyola et al. 2014). Based on these studies, we can assert with high confidence (*sensu* Mastrandrea et al. 2010) that there is a high risk of biodiversity loss in the Atlantic Forest, including species extinction, due to climate change.

A number of studies predict a reduced effectiveness of the network of protected areas in the Atlantic Forest under climate change (e.g., Meyer et al. 2014; Lemes et al. 2014; Ferro et al. 2014; Beltramino et al. 2015; Giannini et al. 2015; Lourenço-de-Moraes et al. 2019; Silva et al. 2019). Systematic conservation planning that takes climate change into account, however, can minimize future loss of species in protected areas throughout meaningful guidance for protected areas network expansion (Vale et al. 2018; Vasconcelos and Prado 2019; Lemes and Loyola 2013). Protection of forest remnants alone will not suffice, however, and well-planned forest restoration is a necessary complementary action to safeguard the Atlantic Forest's biodiversity under climate change (Giannini et al. 2015; Zwiener et al. 2017b).

Despite a large number of studies projecting climate change impacts on the Atlantic Forest's biodiversity, there are substantial taxonomic and methodological bias, which generate significant knowledge gaps, particularly on altitudinal, freshwater, and coastal environments. Given the complex topography of the Atlantic Forest, the lack of observational studies and scarcity of predictive studies (see Hoffmann et al. 2015) on climate change impacts on high-altitude environments and mountain species is surprising. Mountain species and environments are well known for their high vulnerability to climate change both worldwide (La Sorter and Jetz 2010; Öztürk et al. 2016) and in Brazil (Scarano et al. 2016; Fernandes et al. 2018, but see Esser et al. 2019). Several studies have observed range shifts and reduction in mountains. These studies typically replicate altitudinal gradient studies at the community level carried decades ago, revealing upward range shifts and contraction (e.g., Forero-Medina et al. 2011), and could be carried out in the Atlantic Forest. The lack of studies on observed or predicted climate change impacts on Atlantic Forest freshwater ecosystems is also worrisome, given their high diversity and vulnerability (Collen et al. 2013; Roland et al. 2012; but see Esser et al. 2019). Finally, the Atlantic Forest has many associated coastal ecosystems, such as restingas and mangroves, which are also vulnerable to climate change, especially sea-level rise, but there is blatant lack of studies on the topic (Godoy and Lacerda 2015; Oliveira et al. 2016; Copertino et al. 2010). The review of Godoy and Lacerda (2015), for example, reveals that, taking into consideration climate change alone, mangroves in most areas will display a positive response. However, mangroves in southeastern Brazil, which are in constrained coastlines, will most probably not survive (Godoy and Lacerda 2015).

12.3 Adaptation Strategies

Climate change and deforestation are the main causes of biodiversity loss in terrestrial ecosystems in the present and the near future. In addition to contributing individually to biological degradation, the interaction between these factors induces negative feedbacks on ecosystem resilience and contributes synergistically to biological degradation at species, genetic, and/or habitat level. However, reversing current and estimated trends of climate change effects on biodiversity is a socio-ecological problem.

We need to perceive the Atlantic forest as an inherently human-nature coupled system, rather than social and natural systems separately. Within the domain of the Atlantic Forest, we find both some of Brazil's largest urban centers (such as Rio de Janeiro and São Paulo) and more than half of the land dedicated to horticulture and food production (Joly et al. 2014). Forest is no longer the norm in the landscape; it is mostly a collection of small vegetation remnants surrounded by a matrix of urban and agricultural ecosystems (Rezende et al. 2018a).

Given this situation, using ecosystems to promote societal adaptation to climate change is particularly appropriate for the Atlantic Forest (Scarano and Ceotto 2015). Ecosystem-based adaptation to climate change (EbA) is defined by the Convention on Biological Diversity (CBD 2009) as "the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people to adapt to the adverse effects of climate change." One can then expect that a successful EbA program could improve livelihoods across the Atlantic Forest by implementing actions related to ecosystem conservation and restoration (Scarano 2017, 2019).

Although current political and economic instability are obvious hurdles (Loyola 2014; Dobrovolski et al. 2018), recent optimism with EbA applied to the Atlantic Forest has to do with several factors: (1) Favorable legal background that makes mandatory restoration and conservation within private properties to pay for environmental debt; (2) Favorable legal background, in the shape of payment for ecosystem services (PES) legislation in many federal states covered by the Atlantic Forest, to fund restoration; (3) Existence of successful case studies related to PES in several states covered by the Atlantic Forest states; (4) the presence of influential civil society organizations acting in issues related to climate change, conservation, and restoration, such as the Atlantic Forest Pact; (5) Presence of strong academic institutions; and (6) Existence of thriving on-the-ground experiences in project implementation (Scarano and Ceotto 2015; Brancalion et al. 2016; Scarano 2017).

The favorable scenario is such that it has led to a discussion on the possibility of the Atlantic forest gradually change its status from "shrinking biodiversity hotspot" (Ribeiro et al. 2011) to "future climate hope spot" (Scarano and Ceotto 2015; Rezende et al. 2018a). For instance, many municipalities with high legal vegetation debt also have high poverty and/or low human development index, such as those in the northern portion of the state of Rio de Janeiro (Rezende et al. 2018b) or those in the Rio Doce valley, in the state of Minas Gerais (Pires et al. 2017). In such cases, economic incentives must apply in order to foster local restoration-based economies. The injection of resources through mechanisms like PES, for example, could strengthen the economic chain of restoration in degraded municipalities – from the production and commercialization of inputs to the implementation of restoration in the field – stimulating job generation and boosting the local economy while restoring the vegetation. The state of Espírito Santo, for instance, has legislation that ensures the redirection of 3% of oil revenues – so-called "royalties" – to fund restoration (Sossai et al. 2016). If applied in the state of Rio de Janeiro, for example, a similar program would have an annual budget of around USD 40 million, based on 3% of 2016 royalties collected by the state government, not considering the amounts collected by the municipalities (Rezende et al. 2018b). This figure covers the annual costs of planting 39% of the environmental debt in private rural properties of the state, considering 20 years (Rezende et al. 2018b). In the case of the Rio Doce valley, funds from compensation and fines owing to a major spill of mining tailings could also cover large areas with forest restoration (Pires et al. 2017).

Beyond restoration, forest conservation is also a critical component to safeguard biodiversity and the ecosystem services it provides and to foster economy. Protected areas contribute to climate change mitigation. By mitigating the emission of CO_2 and other greenhouse gases resulting from the degradation of natural ecosystems, protected areas help to prevent the increase in the concentration of these gases in the atmosphere. These areas also play a crucial role in protecting strategic resources for the development of the country. For example, Young and Medeiros (2018) estimated that ecosystem services delivered from protected areas generate economic contributions that significantly exceed the amount that has been allocated by public administrations to the maintenance of the Protected Areas System in Brazil. They also found that 80% of the country's hydroelectricity comes from generating sources that have at least one tributary downstream from a protected area; 9% of the water for human consumption is directly captured in protected areas, 26% is taken in sources downstream of them, and 4% of the water used in agriculture and irrigation is taken from sources in or downstream of protected areas. Finally, the authors argue that public visitation in Brazil's 67 national parks has the potential to generate between R$ 1.6 and 1.8 billion per year, considering the estimated flows of tourists projected for the country. Protected Areas in the Atlantic forest have enormous potential in all these fronts, and expanding its network in the region represents a crucial joint objective to provide synergy between climate change mitigation and adaptation (Locatelli et al. 2015, see below).

It has been argued that climate change adaptation (Agrawal and Lemos 2015) and EbA in particular (Pant et al. 2015; Scarano 2017; Kasecker et al. 2018) can often be an essential step in the transition from a conventional to a sustainable development paradigm. Moreover, sustainable development can both be the cause and consequence of mitigation and adaptation to climate change, but only rarely, the links between these processes are examined in an integrated fashion (see Agrawal and Lemos 2015; Scarano 2017).

The conservation and restoration of natural ecosystems, and in particular forests, are prone to bring together mitigation, adaptation, and sustainable development (e.g., Locatelli et al. 2011; Thornton and Comberti 2017; Strassburg et al. 2019). Trade-offs have also been reported, for instance, between carbon sequestration and biodiversity values, local livelihoods, and tenure security (Ingalls and Dwyer 2016). Nevertheless, careful planning for restoration in the Atlantic forest can optimize costs, biodiversity conservation, and carbon mitigation, which altogether might result in climate change adaptation (Crouzeilles et al. 2015; Zweiner et al. 2017b; Strassburg et al. 2019).

Locatelli et al. (2015) described three processes whereby mitigation and adaptation synergy may take place. The first process is "joint outcome," i.e., activities that are undertaken without climatic objectives that deliver joint adaptation and mitigation outcomes. For instance, in the Atlantic Forest, and Brazil as a whole, indigenous lands are designed for human and land rights and cultural preservation. These areas also play an essential role in protecting threatened species (Ribeiro et al. 2018). However, the 1.2 million hectares of indigenous lands in the region (Pinheiro et al. 2014) are also important for carbon mitigation and climate change adaptation (see Walker et al. 2014; Nogueira et al. 2018). The second process is called "unintended side-effects," whereby activities aimed at one climate objective, either mitigation or adaptation, can deliver outcomes for the other objective. For example, actions that target disaster risk reduction and climate change based on ecosystems may often have a mitigation effect of carbon stock or sequestration. This is the case of conservation or restoration of mangroves and sand dunes to avoid coastal erosion (Scarano 2002, 2009) or of hillside forests to avoid landslides (Brancalion et al. 2016; Renaud et al. 2016). Finally, the third process is "joint objectives" and refers to the association between adaptation and mitigation objectives in a climate-related activity. Activities such as ecosystem restoration, payment for ecosystem services, and climate-smart agriculture, among others, are increasingly designed to achieve both goals, often resulting in sustainable development (see Harvey et al. 2014; Kasecker et al. 2018). The potential for synergy between mitigation and adaptation has been estimated based on the presence or absence of four enabling conditions for integration: policies and strategies, programs and projects, institutional arrangements, and financial mechanisms (Duguma et al. 2014). This potential is measured by a score, and these authors found that Mexico (with a score of 8) has the most enabling conditions for synergy between mitigation and adaptation in Latin America, followed by Brazil (7), Ecuador (5), and Chile (4). In all these countries, ecosystems are a key piece in the potential for synergy, and in Brazil, owing to its capacity and available infrastructure, the Atlantic Forest has the highest potential. This is the reason why the Atlantic Forest is increasingly perceived as a biodiversity hotspot that can upgrade to the status of a "climate hope spot" (Scarano and Ceotto 2015; Rezende et al. 2018a, b): a biome that becomes an example that the path of degradation and extinction can be transformed to one of prosperity for humans and nature alike.

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