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RESEARCH ARTICLE

Plausible ecosystem responses to climate change: The case of vegetation in the Lesser Antilles

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Abstract

On all spatial levels, the contrasting topography of the Lesser Antilles represents a great number of biotopes. From the different species to the landscapes, including the phytocenoses and ecosystems, the multiple forms of flora organisation are one of the primary consequences. Despite strong anthropisation, this archipelago is an important component of a *hotspot* of global biodiversity: the land surrounding the Caribbean Basin. Climate change will have long-term consequences on vegetation spatial distribution, species'functioning and plant formations.

Introduction

During the 17thcentury, the takeover of the Lesser Antilles quickly led to the decline of the pre-Colombian forests. The economy that developed, also known as the "habitation or plantation" system, was linked to speculative cultures corresponding to extensive agriculture. From the mid-18th century to the 19thcentury, all the farmable land was occupied by plantations and more marginallyby gardens intended for food production. As a result, the pre-colonial climax forest floor had strongly declined to the point of "insularisation."Today, the vegetation is primarily composed of shrubby, herbaceous or mixed (herbaceous/shrubby) communities, as well as pre-forest communities. However, thanks to the flora diversity, the architecture, structure and functioning of these biocenoses, this archipelago is an important component of a *hotspot* of global biodiversity: the land surrounding the Caribbean Basin (UICN[1]-ONERC ; 2008; Gargominy, 2003).

The naturalhazards, of variable occurrence, have always served as structural elements for both the physical and biological environments, as well as for societies. From the first clearings to the present day, the somewhat anarchic and sectorial socioeconomic organisation and infrastructure-as well as population growth-have only underlined the effects of natural phenomena. These islands have become land attelluric, climatic and ecological risk.

Few articles in the scientific literature discuss the likely or expected mid- and long-term consequences of climate change on island ecosystems, the most frequentbeingthe fragility of the coastline in terms of the rise in sea level . However, the geographic location of the Lesser Antilles, their reliefs, their climates make their ecosystems

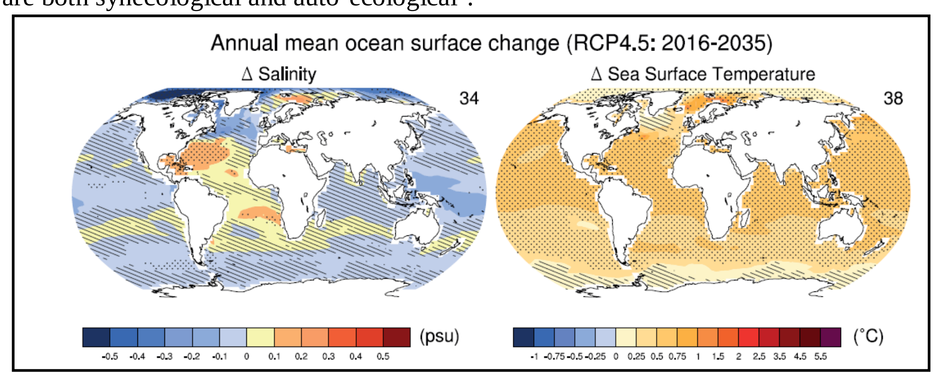
[1] UICN: International Union for Nature Conservation.

subject to the effects of global warming, most notably in mountainous islands where the level of precipitation in high altitudes is the area's main bioclimatic feature. As a result, any future variations of atmospheric humidity-and therefore precipitation- should influence the chorology of thespecies, how they associate and the density of their populations.

The Lesser Antilles are a result of the ancient and recent arcs from intra-oceanic subduction (Biju-Duval *et. al*., 1984). The arrangement of geological structures is linked to the geodynamic phenomena of each island, resulting in a great deal of topographic diversity involved in the great heterogeneity of the biotopes. The general climate, which is practically identical at all points in the Caribbean, is specifically modified by the different island reliefs. At the core of each "island system," the spatial variations of the main factors are specific: wetness, temperature, water loss, cloud covering, exposure to sunlight, humidity, and wind. All the components of this archipelago can be categorised among the different "*materials of factorial constraints*" subsequent to the interaction of these factors, in which wetness is the predominant parameter.The mountainous islands exhibit altitudinal precipitation gradients that define these bioclimates. The bioclimatic zonation of the vegetation levels corresponds to the ecotones (ecosystem interfaces), which vary based on the slopes. In fact, with the coastline at a distance of approximately 800–900 metres, depending on the islands and the facades the variance in precipitation determine the types of vegetation ranging from dry to damp.

Throughout the 21stcentury, it is increasingly plausible that global climate change will become an important factor in redefining boundaries of the biosphere and ecosystem dynamics (Buckley and Jetz, 2007; Maley, 1973; Foley et al., 2000). The changes in physical-chemical characteristics of the atmosphere subsequent to current global warming will affect the distribution of temperatures[2] and pressures (Bengtsson, Hodges and Roeckner, 2006; Emanuel, Sundararajan and Williams, 2008). The climatic dynamic risks being disrupted on both a global and regional scale[3] (Pachauri and Reisinger, 2007; IPCC, 2013). Contrary to the case of the ocean, in terms of polar glaciers and continental glaciers, the effects on vegetation are more difficult to predict (Toby Pennington and Pendry, 2000). Nevertheless, studies show that the biogeographical limits of certains pecies and even of certain ecosystems have varied greatly over the course of the past century, in addition to the process linked to morphogenesis and phenological cycles[4] (Parmesan and Yohe, 2003). However, no observation or precise reference has been made in relation to the present and future consequences of climate change on the flora of theLesser Antilles.

We have deduced the potential ecosystem, biocenotic and possible specific long-term climate change modifications, thanks to our knowledge of the relationships between the island systems' bioclimates and vegetation (Joseph, 1999; Fiard, 1994) and the conclusions reached by the IPCC[5], which predict a decrease in precipitation in the Caribbean and American Tropics region in the short-, mid- and long-term (UICN-ONERC, 2008; Pachauri and Reisinger, 2007; IPCC, 2013; Figures 1-2). The elements taken into consideration include: the structure and architecture of the populations, the spatial distribution of the species (their chorology), and their dynamics, which are both synecological and auto-ecological[6].



[2]According to the IPCC experts, the temperature of the Earth's surface from now to the year 2100 should be between 1.8 °C and 4° C. In the Caribbean, the projected average temperature increase is 2°C (between +1.8 and + 2.4).
[3]Climate change is a complex phenomenon because anthropic greenhouse effects combine with natural greenhouse effects.
[4]The phenological cycles correspond to the species'biological cycles and phytocenoses.
[5]Intergovernmental Panel on Climate Change.
[6]Synecology is an area of ecology that studies biocenosis while auto-ecology deals with issues related to a single species.

Figure 1: CMIP5 multi-model ensemble mean of projected changes in sea surface temperature (right panel; °C) and sea surface salinity (left panel; practical salinity units) for 2016–2035 relative to 1986–2005 under RCP4.5. The number of CMIP5 models used is indicated in the upper right corner (IPCC, 2013.)

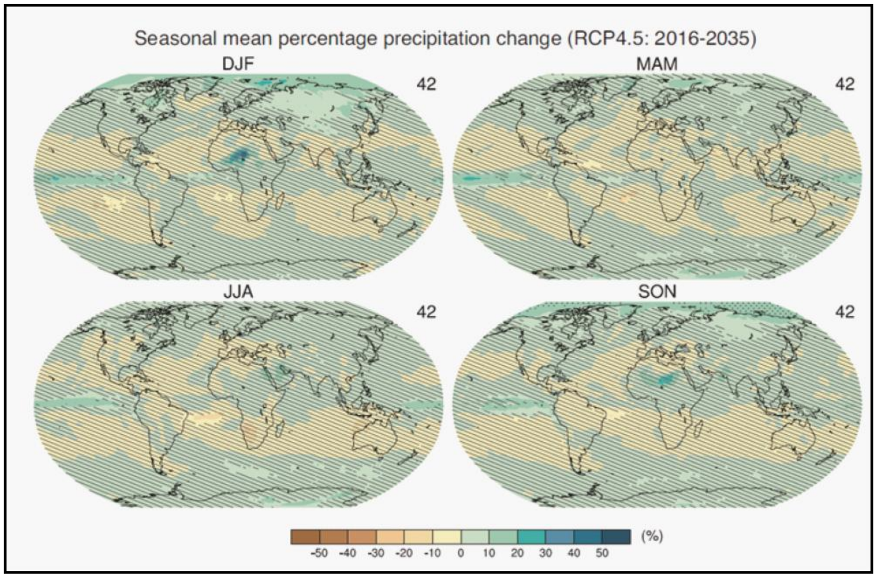


Figure 2**:** CMIP5 multi-model ensemble mean of projected changes (%) in precipitation for 2016–2035 relative to 1986–2005 under RCP4.5 for the four seasons. The number of CMIP5 models used is indicated in the upper right corner (IPCC, 2013.).

The primary features of the original vegetation

The Caribbean forms part of the Neotropical flora region and its constituent geographical entities, which have strong taxonomic similarities, mostnotably in terms of families. The vegetation of the Lesser Antilles can be determined by the eco-climatic conditions and specified by strict flora varieties in the area. The volcanic islands are home to all the observable vegetation cover on the archipelago, whatever their stage of evolution and spatial extension. On a large scale, there is a certain correlation between the spatial limits of the bioclimates and the primary potential types of wildlife. The data on the vegetation and human practices of the pre-Colombian time period permit the irrefutable confirmation that the vegetation cover was purely forest-basedand highly complex. It is entirely possible that during the prehistoric period, despite the presence of the Amerindians, the majority of forest formations reached the end of their evolution: the climax stage (Fiard, 1994; Joseph, 1997).These islands comprised a notable centre for numerous plant species (Figure 3). Martinique is the farthest removed island from the centres of dispersion (Greater Antilles and Tropical America) and characterised by a more pronounced endemism.

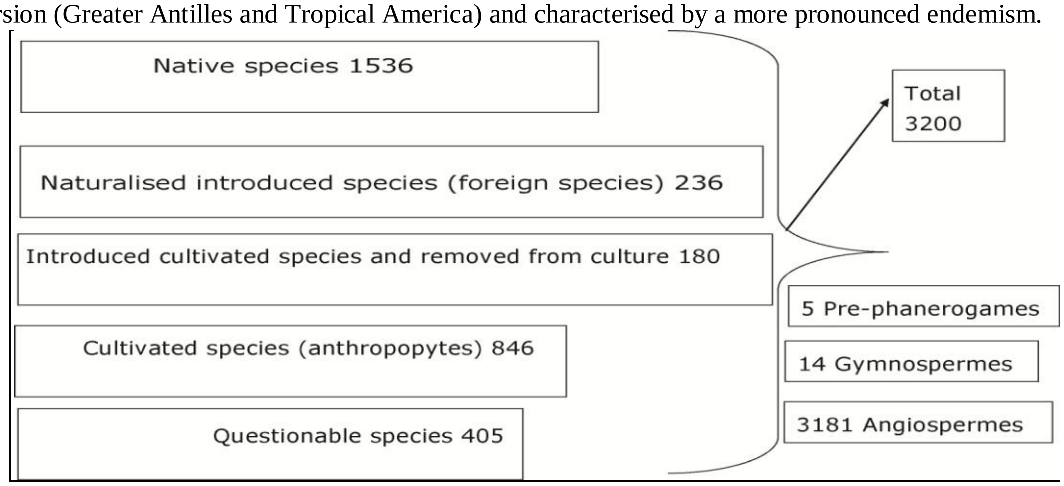


Figure 3: Certain elements of the flora diversity of the Lesser Antilles

The lower, middle and upper vegetation levels of the mountainous islands are situated respectively between 0 and 250 m, 250 and 500 m, 500 and 1300 m and above. They are influenced by dry, moderately humid and extremely humidbioclimates in which the annual average rainfalls are 1500 mm, 1500-2500 mm, 2500-4000 mm and 4000 mm and above (Figures 4 a,b). Wecan find, respectively, according to increasing altitude:

The tropical evergreen seasonal forest with a lower horizon and xeric features (xerophilous forest), the tropical evergreen seasonal forest (mesophilous forest), the tropical ombrophilous submontane forest (hygrophilous forest), and the tropical ombrophilous montane forest (hygrophilous montane forest. These original forest types are associated with collections of plant species that are not necessarily identical between the different islands. The ensemble forms the collection of flora species of the Lesser Antilles or global potential flora (Figure5). In addition to the aforementioned forest types, there are also those that occur in the presence of transitional areas or ecosystem boundaries between the lower and middle levels or even between the middle and upper levels. The following are included in this category (Fiard, 1994; Joseph, 1997 and 1998):

- the *tropical ombro-evergreen seasonal forest (hygro-mesophilous forest)* developed with the interface or the intersection *of ombrophilous montane and evergreen seasonal forests,*
- the intermediate form in the order of *ombro-ombrophilous submontane* are situated on the upper level between the *ombrophilous montane and ombrophilous submontane forests* colonising a marginal altitudinal fringe (*unpublished personal data*).

Despite their physionomic and functional similarity, the potential forest groups of the different islands are quite distinct. In fact, within the same vegetation level, the diversity of biotopes results in a wide range of variable flora preponderances.

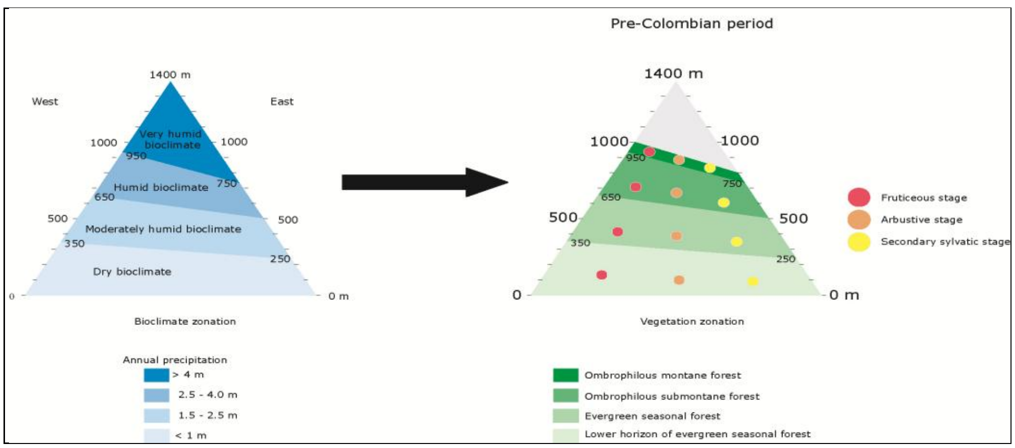


Figure 4a: Potential ecosystems and bioclimates (mountainous Lesser Antilles)

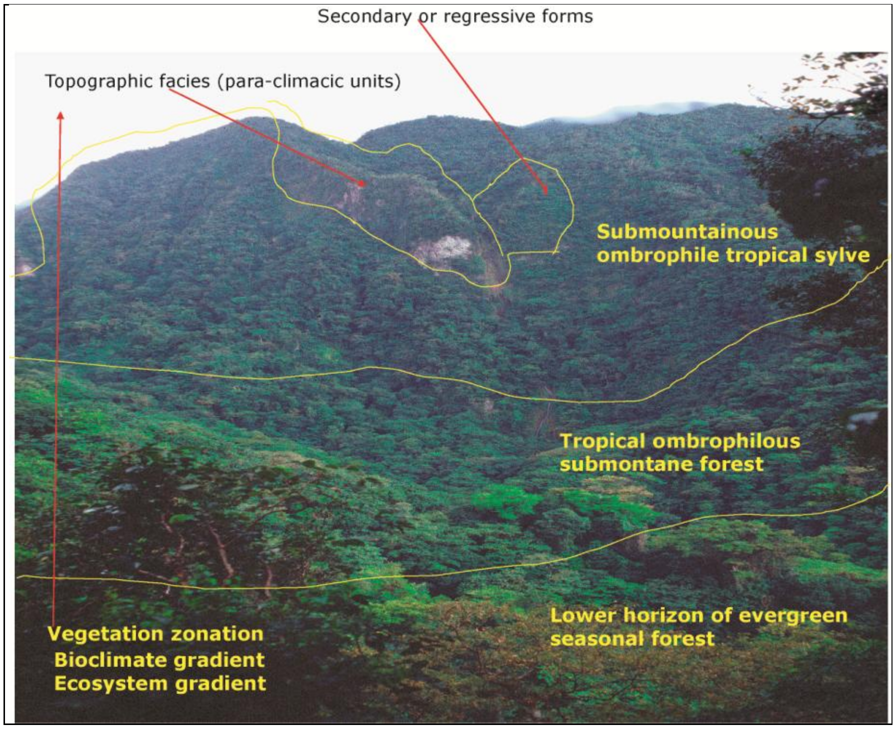


Figure 4 b: Example of vegetation zonation

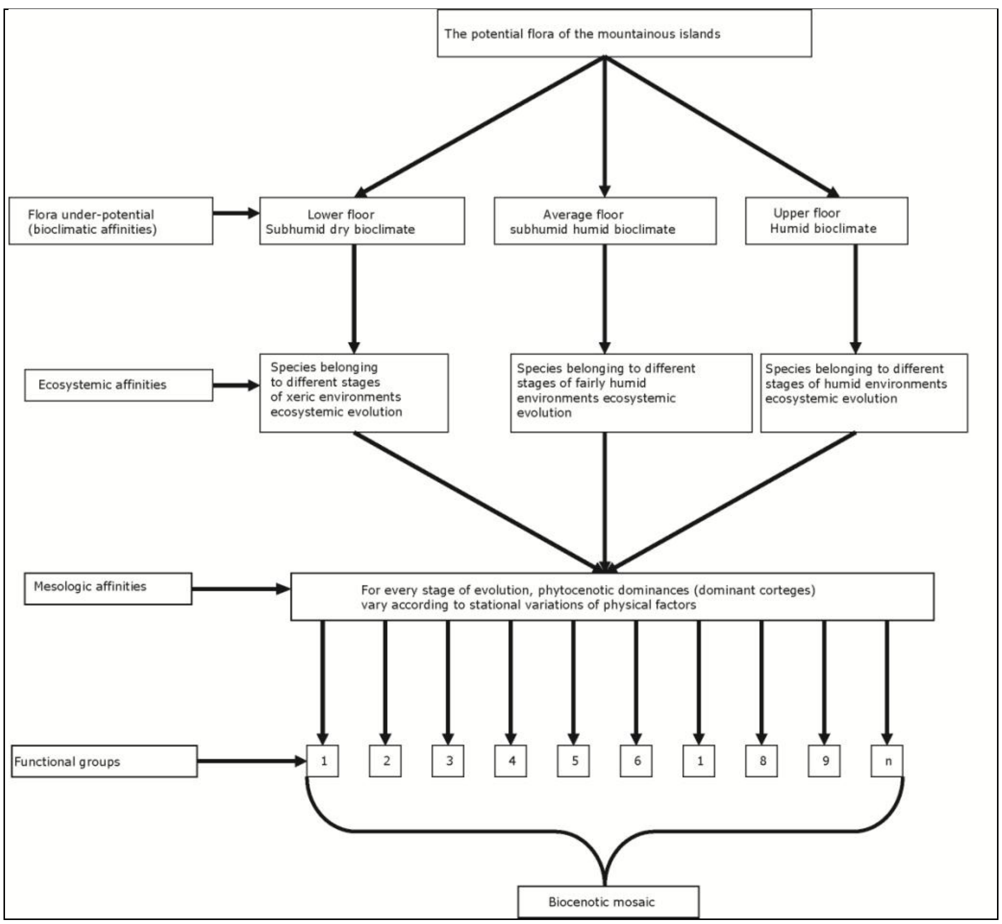


Figure 5: The different aspects of potential flora of the mountainous islands

The current state of plant ecosystems

The observable and diverse physionomic entities in today's landscape are merely forms of decline of the original forests (Joseph, Pagney and Tanasi, 2003). Their degree of organisation is variable and depends on the anthropic history of each site. In fact, the human activities over the centuries have established, and essentially sustained, a secondary vegetation: dry and tropophilous forests, open forests, pre-forest formations, grassy tree formations, grassy shrub formations, shrubby formations, grass and herbaceous formations, etc. (Joseph, 2006a, 2007, 1998; Figure 6).

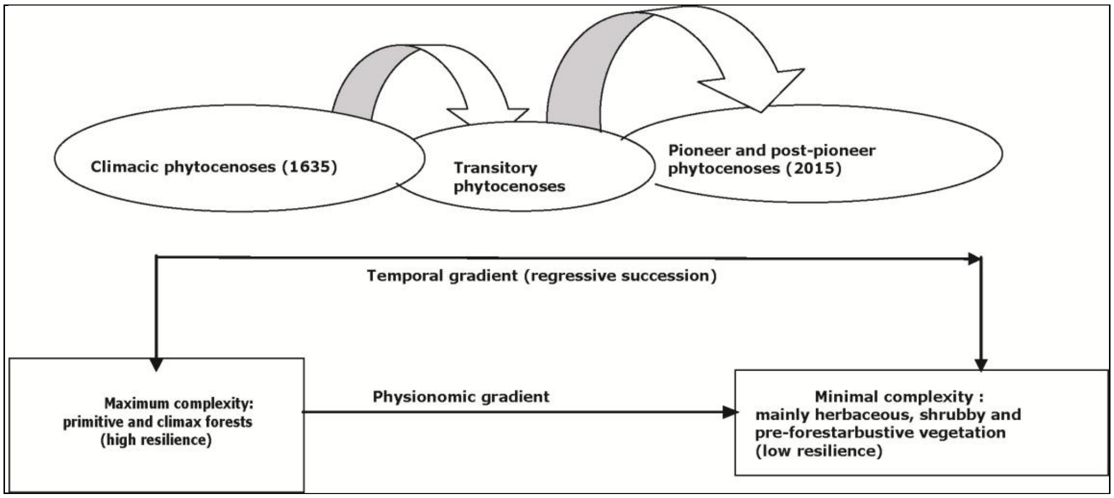


Figure 6: The vegetation presents a mosaic of ecological profiles

In addition to this anthropic vegetation, there is flora of cultures ("anthropophyte" flora). The creates a very diverse landscape, interweaving altered flora communities pertaining to the different temporal phases. As a result, the Lesser Antilles comprises a mosaic of altered ecosystems in the present day. The original biodiversity and the biodiversity affected by human intervention establish these minuscule regions *in situ* in the laboratory, where the functional processes can be more easily approached and understood, notably the different phases of vegetation dynamics (Shugart, 2003; Williamson, 1997).We have determined approximately 10 stages of succession for dynamics associated with the intermediary sequences (Joseph, 2004a - Figure 7).

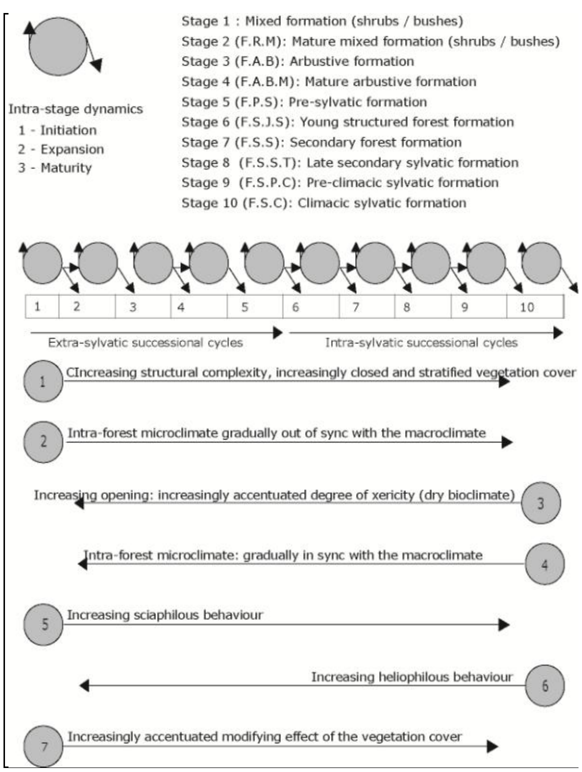


Figure 7: The dynamic gradient

Plausible modifications linked to global climate change

The decrease in rainfall anticipated for the Caribbean Basin from the present time until the year 2100, according to the IPCC's models (Pachauri and Reisinger, 2007; IPCC, 2013.), is between 3 and 19% and perhaps even much greater (Campbell *et. al.*, 2011; Figures 8 & 9). The decline of orographic precipitation could lead to the biotopes drying up. In fact, the lower level influenced by the dry bioclimate determining the development of the "tropical evergreen seasonal forest with a lower horizon and xeric features" will become increasingly morexeric. The middle and upper levels, delimited by moderately humid and humid bioclimates,will progressively lead to a decrease in precipitation resources and humidity.

If we consider the simulations of the IPCC (2013) and Campbell et al. (2011), by extrapolation, this trend could continue in the long-term with the consequence of the dry season having a longer duration than the rainy season (IPCC, 2013; Campbell *et al*., 2011). In this case, these islands will progressively change from a tropical humid system to a tropical dry system, well beyond the end of the first century of the 3000s. This phenomenon will be aggravated by the significance of the dry season, inter-annual climatic variations and forms of anthropisation[7]. Precipitation is the main determining factor of the vegetation's spatial organisation, and the structural modifications of the precipitation gradient will lead to new altitudinal limits of vegetation levels (Figure 10).

[7]These parameters are hard to predict at the present time.

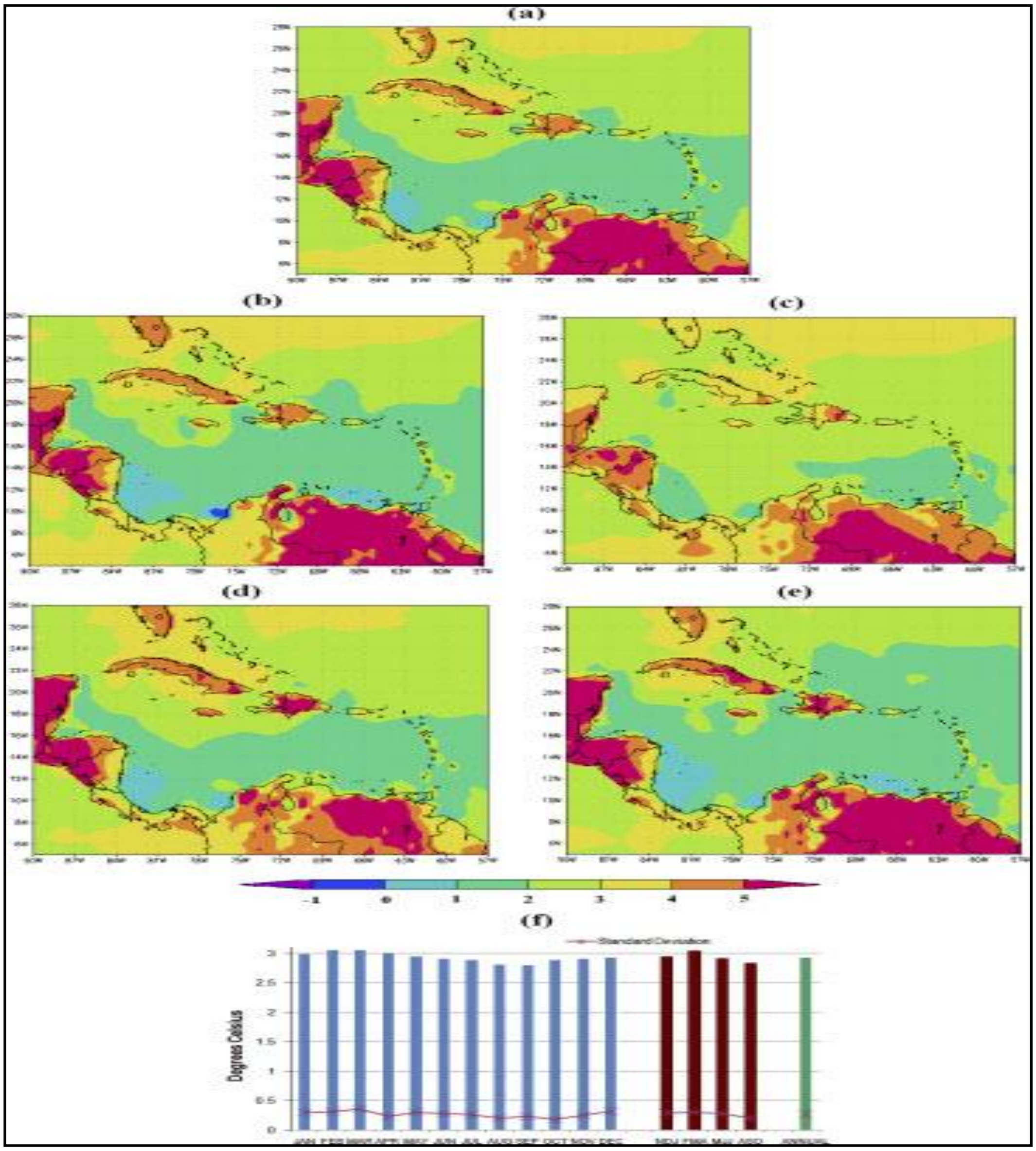


Figure 8: Temperature projections for the period 2071–2100 relative to the period 1961–1990 baseline under the A2 scenario. Absolute change is presented. Panels (a), (b), (c), (d) and (e) represent annual, NDJ, FMA, MJJ and ASO, respectively. Panel (f) shows monthly, seasonal and annual changes calculated by averaging over the domain shown in (a)–(e). The solid line represents one standard deviation as calculated from the NCEP–NCAR reanalysis data set (Campbell, et al., 2011).

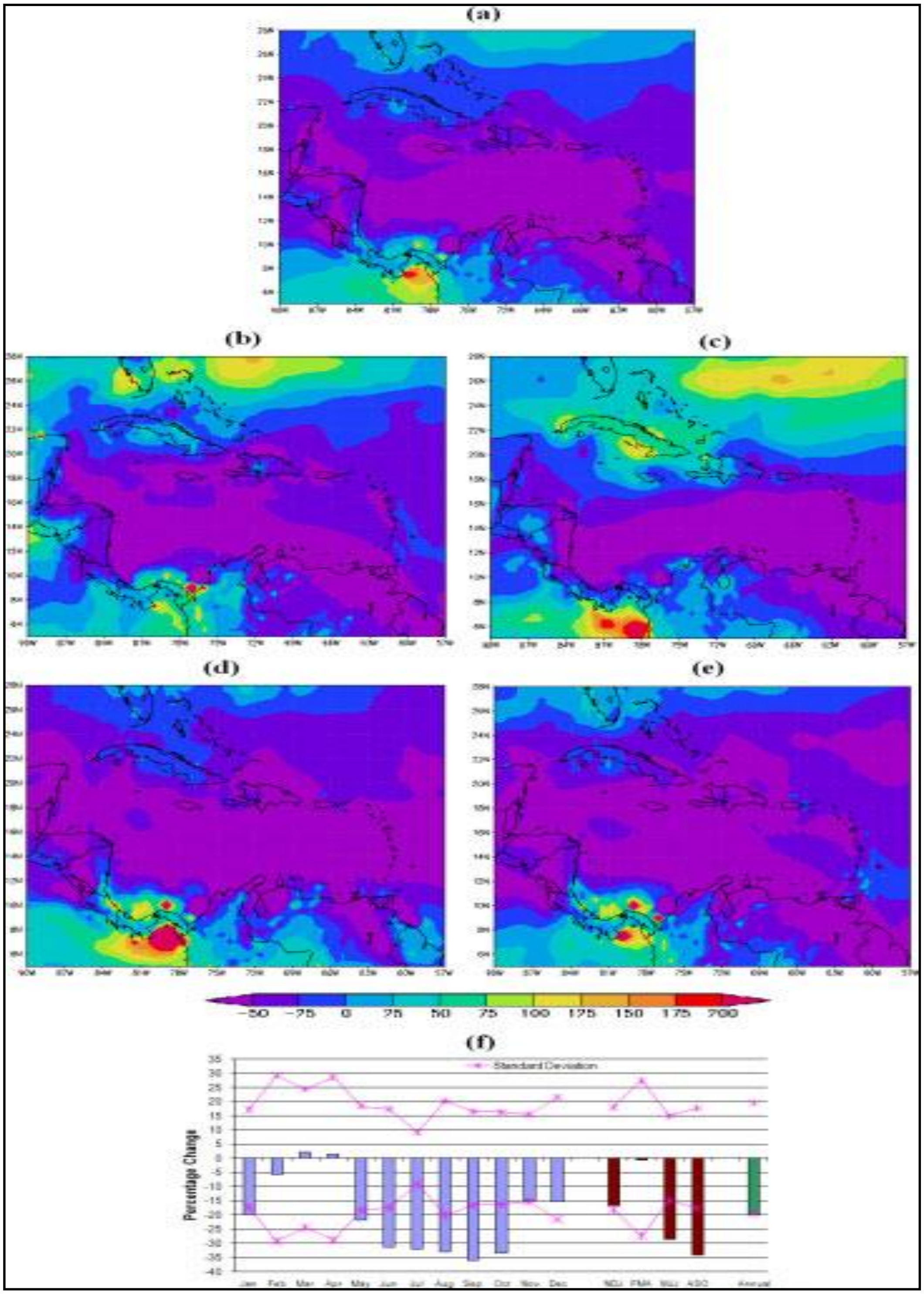


Figure 9: Rainfall projections for the period 2071–2100 relative to the period 1961–1990 baseline under the A2 scenario. Percentage changeis presented. Panels (a), (b), (c), (d) and (e) represent annual, NDJ, FMA, MJJ and ASO, respectively. Panel (f) shows monthly, seasonal and annual changes calculated by averaging over the domain shown in (a)–(e). The solid line represents one standard deviation as calculate from the CMAP dataset (Campbell, et al., 2011).

In the absence of a noticeable reduction of anthropic emissions of carbon dioxide, the continued drying up of this geographic region will lead to a sort of transfer or shift of the bioclimates in the direction of the higher altitudes[8]. In the extreme long-term, only the dry and moderately humid bioclimates will persist since the precipitation will be insufficient to produce the humid and extremely humid bioclimatesin the upper third level of these moderate mountains (Figure 10). In a consubstantial way, the primordial ecological conditions for the development of the potential forest types will undergo the same spatial redistributions due to a modification of the plant species' chorology (their spatial distribution).

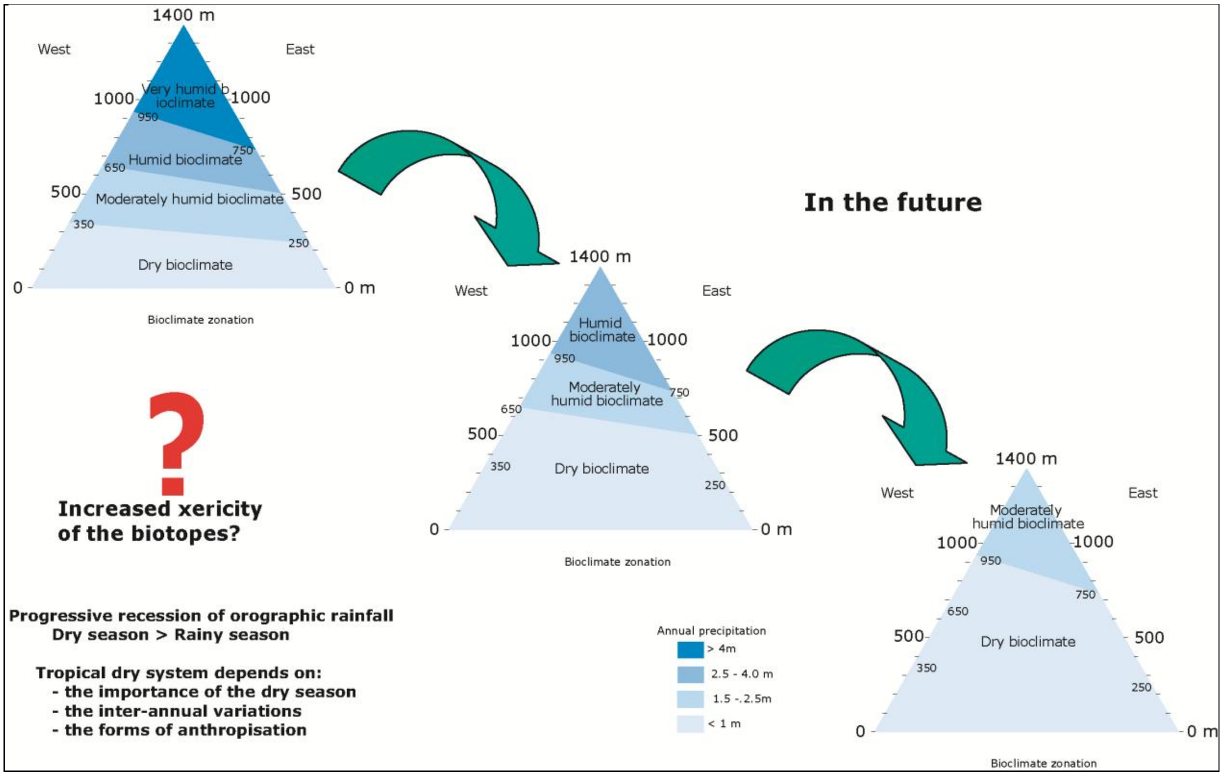


Figure 10: Altitudinal transfer of the bioclimates

In the long-term, the ombrophilous montane forest types and ombrophilous submontane (hygrophilous forests) risk disappearing or occupying marginal surfaces in lieu of a very significant altitudinal extension of the evergreen seasonal type with a lower horizon (xerophilous forest). From this perspective, the seasonal evergreen forest type (mesophilous forest) would occupy a narrow strip of the summit of the mountains (Figure 11). In fact, it is highly likely for "insularisation" of the ombrophilous and mesophilous flora to occur in parallel with a potentiation of the species of xerophilous flora from the secondary dynamic levels since the current centres of the lower level are regressive. Generally speaking, we can expect a population dominance and therefore ecological dominance of the xerophytes and, furthermore, the mesophytes[9]. This process, if it occurs, would correspond to a biocenetic and ecosystemic adaptation to the possible precipitation reduction in this part of the world. The vegetation's ability to adapt in the Lesser Antilles is conditioned to their processes of self-organisation, which define their degree of resilience. The modifications of the spatial distribution and the relationship with the taxa's population dominance will have consequences on the evolutional processes of the flora dynamics.

[8]This will occur according to varied spatial extensions.
[9]The mesophytes and xerophytes are distinctively typical of moderately humid and dry bioclimates.

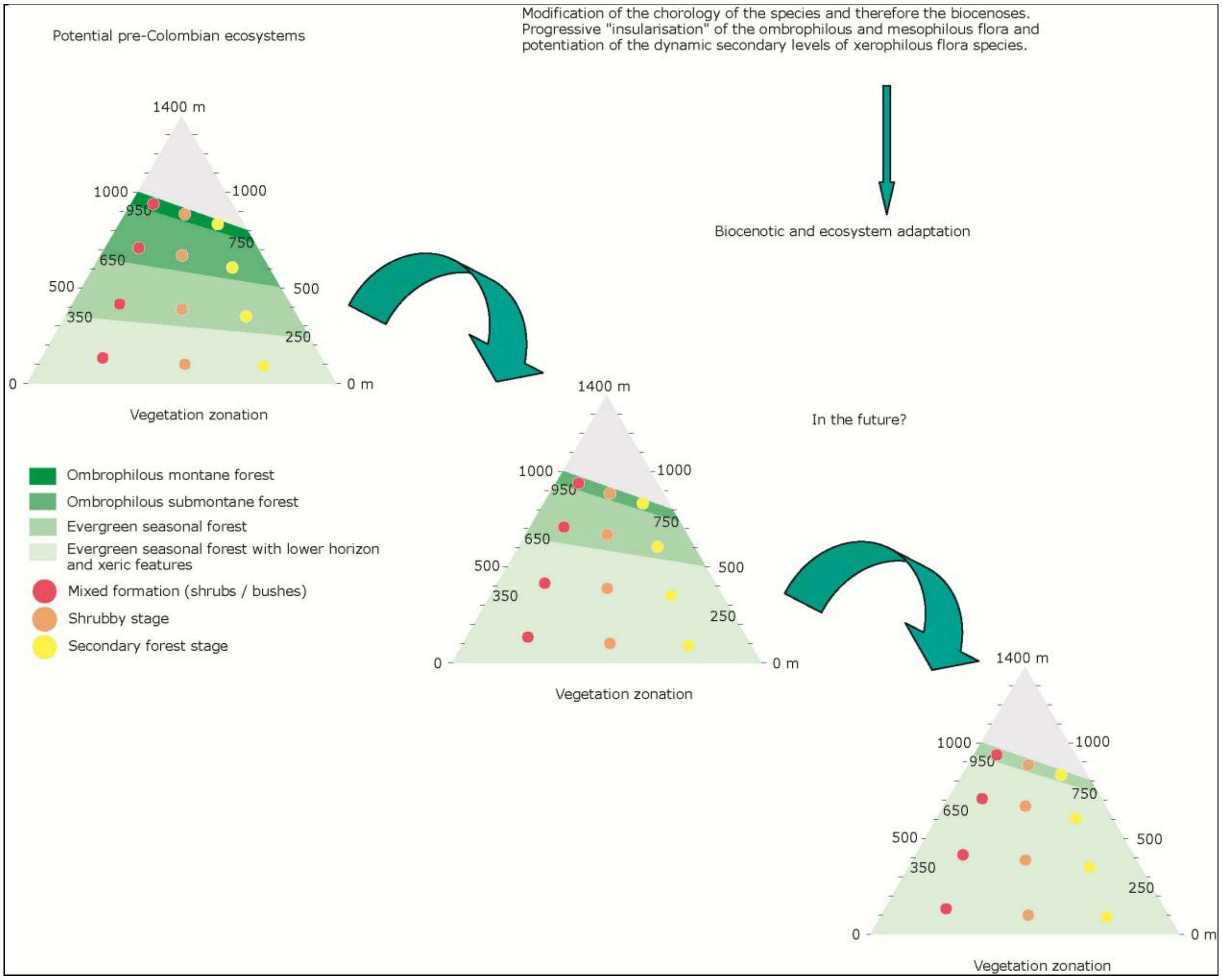


Figure 11: Plausible evolution of the potential ecosystem of the Lesser Antilles

Other phenomena may also be accentuated, such as ones related to introduced taxa becoming intrusive and extreme phenomena such as destructive hurricanes (Turton and Siegenthaler, 2004; Imbert, 2002; Pedersen, Genoways and Freeman, 1996; Bythell, Cambers and Hendry, 1996). In fact, climate change modifying the structure of certain eco-climatic factors such as temperature, rainfall and humidity content, could exaggerate the effects of anthropisation in terms of the introduced species. The decline (anthropic and natural) of the efficacy of the ecological barriers will lead to even greater ecological efficiencyof foreign species, which may become invasive or intrusive (Loope and Mueller-Dombois, 1989; Figure 12). Certain data point in this direction. Often after violent hurricanes have transformed the structure and architecture of tropical island plant formations, certain naturalised species develop from highly dense populations. They become ecologically dominant and have the tendency to modify the biotope's characteristics by improving the ecological success of their regeneration (Joseph, 2006b; Thomas *et al*., 2004). Logically, the disturbances will be both autogenic[10]allogenic[11]. The justification developed further along only makes sense in terms of the original hypothesis: being aware of a regular decrease in the precipitation over a considerable amount of time. An annual decrease of approximately 12% is predicted by the end of the 21st century (UICN-ONERC, 2008; Pachauri and Reisinger, 2007). The consequences of this decrease on the vegetation cover of the Lesser Antilles constitute a primordial line of research.

Generally speaking, the biodiversity of this archipelago is subject to anthropic erosion. As a result, the impacts of global warming will tend to accelerate the disappearance of habitats and therefore taxons. Whether through coastal flooding, extreme phenomena such as hurricanes, or a population increase of introduced species, the flora of these islands will be profoundly disrupted. To assure their strong resilience synonymous with ecosystem

[10]Autogenic fluctuations are linked to mechanisms of the biosystems' self-organisation.
[11]Disturbances that are external to the ecosystem.

plasticity, it seems necessary to conserve all the forms of plant organisation of the species in the landscape (Joseph, 2004b).

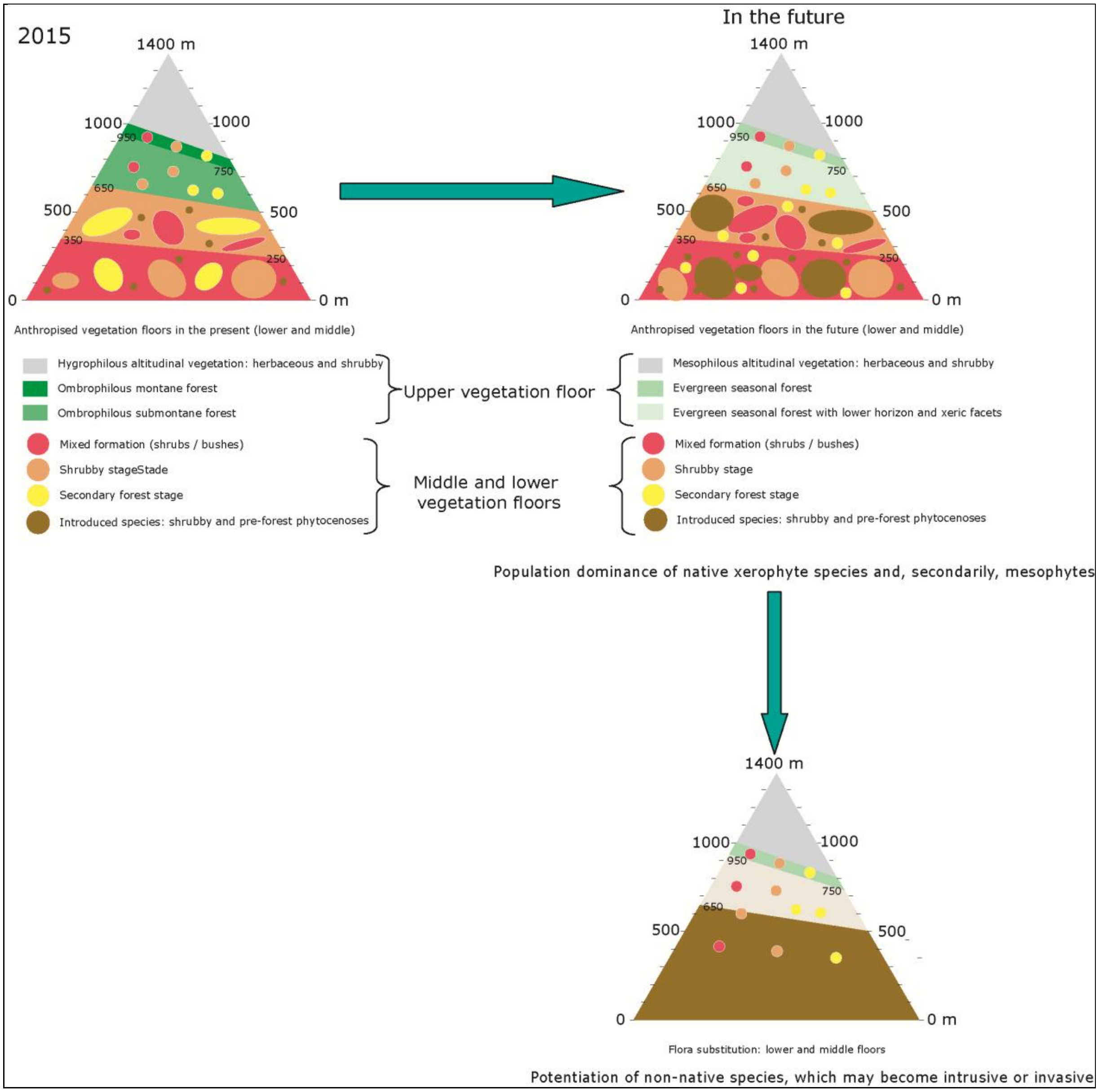


Figure 12, Plausible physionomic, biocenotic and ecosystem evolution

Conclusion

With relatively good structural and functional knowledge of the plant formations in the Lesser Antilles, and in light of the conclusions reached by the IPCC (2013) and Campbell *et al*. (2011), we have proposed a hypothetical vision that does not purport to claimany irrefutable truths. There are many grey areas, notably those related to the uncertainty of the models and simulations of international scientific authorities, which deal with varying aspects of this issue. Bearing in mind the reduced extent of this region, the measurements, analyses and interpretations on a global scale do not allow us to fully answer all our questions. On these small islands, the study of the spatiotemporal evolution of the ecosystems' biodiversity under the constraints of the diverse effects of climate change will allow us to produce relevant dataon a local scale. The goal is to follow the flora and fauna successions, the"interfacial" dynamics between biocenoses, ecosystems and landscapes, as well as the evolution of site-specific climate factors. From the perspective of attenuation and/or adaptation, it will be possible to correlate, on the scale of the Lesser Antilles, the dynamics of anthropisation, biodiversity (native and non-native) and climate change in the mid-term.

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