# **Chapter 16 Monitoring Global Change in High Mountains**

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**Abstract** Long-term ecological research provides essential information to understand the complex dynamics of natural systems. In a global change scenario, high mountains represent an exceptional ecology field lab for long-term research and monitoring, offering an enormous mosaic of ecological conditions existing along mountain slopes. Mountains ecosystems also constitute invaluable observatories of the atmosphere and all the aspects related to climate, atmospheric particle deposition, pollutants, greenhouse gases, or the transport of resistant biological forms. Mountains are sensors for early detection of change. In the Sierra Nevada LTER site (southern Spain), we have been implementing a long-term monitoring programme taking advantage of the high altitude and geographical position of this Mediterranean mountain. We have identified the main expected impacts in the context of global change and analysed the biophysical and socioeconomic data available to assess exposure, sensitivity, and adaptive capacity of ecosystems to future scenarios. The study incorporates a retrospective of past human management of land use, to understand the current state of conservation of the ecosystems and make plausible forecasts on its response to future scenarios. The results show the following: (1) an ancestral human footprint on the ecosystems of Sierra Nevada, particularly evident during the 20th century; (2) a moderate climate warming, with reduction and increased variability in precipitation, as well as a consequent reduction in snow-cover duration during the last few decades; (3) significant changes in biophysical characteristics of rivers and mountain lakes; and (4) shifts in the distribution and phenology of many species of plants and animals along elevation gradients.

**Keywords** Long-term ecological research LTER • Sierra Nevada • Global change monitoring • Mediterranean mountains • Land-use changes

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#### 16.1 Introduction

Mountains are the crown jewels of our natural heritage around the world and yet are locally unique. They provide key ecosystems services particularly sensitive to human impact. The challenge for mountain conservation is to determine ecosystem exposure and sensitivity to environmental changes as well as their ability to adapt to global change in the present and the future (Hansen et al. 2014; Zamora et al. 2016). Despite uncertainties concerning the response of biophysical processes to human impact, there is enough scientific capability to envisage the foreseeable trajectory of major ecological processes and to manage the adaptation of ecosystems to possible future scenarios. In this context, long-term research and monitoring are essential for understanding the dynamics of populations, communities, and ecosystems (Carpenter 1998; Lovett et al. 2007). One of the most prominent examples of a long-term study is the work begun in 1958 in Mauna Loa, Hawaii, which has demonstrated a slow but steady increase in the concentration of atmospheric carbon dioxide (Keeling et al. 1995, 1996)—a trend that continues today and is now investigated through a global network of stations (Battin et al. 2009). Moreover, developing long-time data series is critical for the proper parameterization and validation of environmental models, such as the general circulation models to predict future climate, or related potential changes in species distribution (Burgman et al. 1993; Canham et al. 2003; Berdanier and Clark 2016). Thus, high-quality ecological information collected over extended periods of time can yield valuable insights into changes in ecosystem structure, key ecological processes, and the services provided by ecosystems (e.g. Daily 1997; Lindenmayer et al. 2012).

A full comprehension of many ecological processes requires long-term monitoring because their rate of change is very slow, and/or because extreme events that can have substantial impacts are usually rare (Fahey et al. 2015). Many ecosystems are likely to undergo abrupt changes due to global drivers such as climate change (Barnosky et al. 2012). Designing and implementing large-scale ecosystem management programmes are needed to confront these problems and to provide positive ecological and economic solutions (Pace et al. 2015). Additionally, the use of information from long-term data series enables managers to evaluate and mitigate threats to ecosystem function and services while operating more effectively in the legal and political arenas. This point is important because resource managers, policy-makers, and the general public may be unaware of these values and the critical role of long-term ecological studies in tackling emerging problems of major social concern (Lindenmayer et al. 2012).

# 16.2 Monitoring Global Change in High Mountains: The Case of Sierra Nevada

To understand the consequences of human impact on the planet, we need systems of reference. Mountain ecosystems may represent the best-preserved reference systems in a given region, providing us the opportunity to compare their dynamic

behaviour with anthropic ecosystems surrounding the mountains under a global change scenario (Becker and Bugmann 2001; Huber et al. 2005; Hansen et al. 2014). In this respect, mountain ecosystems are equivalent to controls in the classic experimental designs against which to compare "treatments", in this case, caused by human activities (land-use changes, climatic change, pollution, overexploitation of resources, etc.) in the surrounding anthropic matrix. For example, we can compare the effect of tree species diversity on forest productivity (e.g. Liang et al. 2016) in native mountain forest vs. plantations and/or strongly managed forest in the humanized landscape surrounding the most preserved mountain forest ecosystems.

In a scenario of global change, a high mountain such as Sierra Nevada (Box 16.1) represents an exceptional ecology field lab, offering the advantage of the enormous mosaic of ecological conditions existing along mountain slopes. For instance, the topographic variability of steep mountain slopes creates a multitude of fine-scale environmental conditions that is mirrored in plant species distribution and abundance (Scherrer and Körner 2010, 2011; Scherrer et al. 2011). As a result of this fine-scale spatial distribution, within a short distance, on the same elevation, we can find "Mediterranean", "montane", and "alpine" species depending on the micro-environmental conditions of their habitats (Scherrer and Körner 2010, 2011; Scherrer et al. 2011).

#### Box 16.1 Sierra Nevada

Sierra Nevada (Andalusia, SE Spain) is a mountainous region covering more than 2000 km<sup>2</sup> with an elevation range of between 860 m and 3482 m a.s.l. The regional climate is Mediterranean, characterized by cool winters and hot summers, with a pronounced summer drought (July-August). The annual average temperature decreases in altitude from 12–16  $^{\circ}$ C below 1500 m to 0  $^{\circ}$ C above 3000 m a.s.l. Annual precipitation ranges from less than 250 mm in the lowest parts to more than 700 mm in the summit areas. Additionally, the complex orography of the mountains causes sharp climatic contrasts between the sunny, dry south-facing slopes and the shaded, less-exposed north-facing slopes. This mountain area harbours 27 habitat types of the EU Habitat Directive (92/43/EEC), and it is considered one of the most important biodiversity hotspots in the Mediterranean region (Blanca et al. 1998; Cañadas et al. 2014). Sierra Nevada receives legal protection in multiple ways: it is a MAB Biosphere Reserve, Special Area of Conservation (Natura 2000 network); Natural Park and National Park; and Important Bird Area. Sierra Nevada is included at the World Green List of Protected Areas (IUCN), and is part of the Spanish Long-Term Ecological Research (Zamora et al. 2016). The main economic activities in this mountain region are agriculture, tourism, livestock raising, beekeeping, mining, and skiing (Bonet et al. 2010).

Mountains are far more than just lands at high elevations. High mountains such as Sierra Nevada act as sensors for early detection of signs of change, due to the high elevation and geographical position of this Mediterranean mountain.

This includes processes considered more genuinely global and is precisely the processes that can be observed better from the mountains, as exceptional lookouts. In this sense, mountain ecosystems are key observatories of the atmosphere and all the aspects related to climate such as energy balance, UV radiation, atmospheric particle deposition, pollutants, greenhouse gases, or the transport of resistant biological forms and microorganisms (Beniston 2003; Huber et al. 2005; Zamora et al. 2016).

## 16.3 Conceptual and Method-Related Issues

Given the complexity of natural systems and the variety of factors that influence natural processes, monitoring programmes clearly need conceptual frameworks that help organize the information gathered. These programmes to be effective should be based on well-defined specific questions within a clearly stated framework providing scientific hypotheses and predictable scenarios of change. Otherwise, it could turn into an exercise in "fishing", with the risk of the monitoring programme ending up with a collection (a hodgepodge as broad as the kinds of specialists involved) of pseudo-indicators in which all taxonomic and/or thematic variable entities capable of being measured are jumbled together. In fact, many monitoring initiatives have a narrow thematic scope. In our case, the goal is to identify the best biophysical and socioeconomic indicators of the health of our ecosystems under a global change scenario, and to determine the exposure and sensitivity of ecosystems to environmental changes, and their ability to adapt to global change (Hansen et al. 2014; Zamora et al. 2016). Besides the rigour necessary within a specific scientific framework, a monitoring programme should be guided by human needs, identifying key environmental and economic services that the public receives from ecosystems. In doing so, monitoring programmes are also valuable for society in general as well as to scientists and managers in particular (Lindenmayer and Likens 2009).

The design of the Global Change Monitoring programme in Sierra Nevada has been inspired by the conceptual framework and the thematic areas proposed by the GLOCHAMORE (Global Change in Mountain Regions <a href="http://mri.scnatweb.ch/projects/glochamore">http://mri.scnatweb.ch/projects/glochamore</a> sponsored initiative UNESCO) (Grabherr et al. 2005) and related initiatives. Our monitoring programme is based on evaluating, using standardized protocols, the composition, structure and functioning of the ecosystems of the Sierra Nevada, and its dynamics over the middle to long term. This programme is designed to identify the effects of global change on key biophysical processes in mountain ecosystems, providing a vision of the trends of change that allow the development of an adaptive capacity. The long-term evaluation of ecosystems function and services in a context of global change is a primary aim of our approach. Long-term series collected in our programme will help us to forecast the evolution of our ecosystems under new scenarios, with the use of modelling tools.

Within the monitoring programme, the way to foster cooperation between research groups of the University of Granada (Spain) and other research institutions and managers and technical teams of the Sierra Nevada National Park is through joint work in the thematic areas we have defined as systems of indicators (Box 16.2). For each of the thematic areas of our research strategy, methods have been defined to evaluate both the state of key ecological functions, as well as the possible impacts of global change on ecosystems of Sierra Nevada.

#### **Box 16.2 Thematic Areas**

Climatology

Temporal change in the cryosphere

Palaeo perspective

Land-use and land-cover changes

Atmospheric deposition

Population trends and community changes

Biodiversity changes

Phenological changes

Invasive species

Emerging diseases

Biogeochemical changes in aquatic systems

Primary productivity and carbon fluxes in terrestrial ecosystems

Ecosystem services and socio-economy

Extreme events (wildland fire, floods, landslides)

Assessment of ecosystem management activities

The thematic areas of our research strategy are organized according to our understanding of the causes and consequences of global change, their ecological consequences and the corresponding biotic and socioeconomic responses to changes. For practical organization, each thematic area follows the same logical flow: (1) starting with well-formulated and tractable questions that were posed at the outset of the work, (2) designing high-quality data-collection protocol, with careful attention to field data and field sample storage, and (3) developing collaborative partnerships among scientists and environmental managers.

As far as possible, each thematic area is linked to projects of adaptive management and the development of decision support tools.

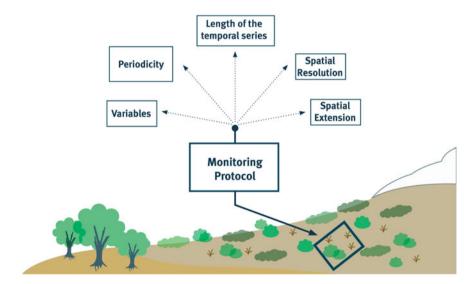
# 16.4 Data Collection Within the Monitoring Protocol

For each of the thematic areas outlined above, a set of monitoring methods has been defined to assess the status of key ecological functions, such as primary productivity, ecosystems functions and services, biogeochemical cycles, etc. (Aspizua et al. 2014). These methods allow us to cover most of the aspects considered to be necessary for evaluating the effects of global change in this mountain region.

Our approach takes into account the high spatial heterogeneity and ecological diversity of the Sierra Nevada mountain range. Data are collected over a hierarchy of spatial scales: fine scale (point and transect data); a somewhat coarser scale but covering the entire space (e.g. pixels of satellite images, polygons of a vegetation map); and administrative boundary scale (i.e. catchment basin, municipality). Also, many of the sampling points that take more detail (points and transects) are spatially aggregated in places with a high density of monitoring protocols.

Our monitoring programme incorporates the temporal dimension from two different perspectives: (1) Historical information (including when possible the palaeo perspective) on the structure and dynamics of the Sierra Nevada ecosystems; and (2) Recent information, focused more on the frequency of data collection. The purpose of the historical reconstruction is to use information about the past in interpreting and understanding the present, and by doing so, try to predict possible future trends. In this regard, it is important to consider the length of the series available for each feature monitored. As with the frequency of the data collection from recent information, we use methods that collect information according to the processes of interest (e.g. periodicities of less than a day (weather stations) to seasonal inventories, or at longer time scales, annually or every several years).

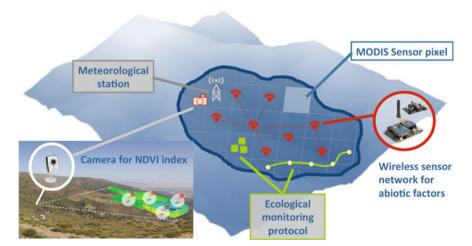
In short, our monitoring programme is composed of a set of scientifically validated protocols that can be described based on a number of attributes, thematic (according to GLOCHAMORE approach), spatial (data-collection scale and the extent of data application), and temporal (length of time series and data-collection periodicity) (Fig. 16.1).



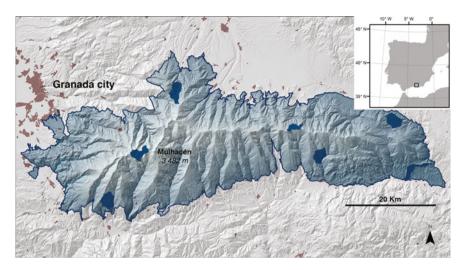
**Fig. 16.1** Thematic representation of the five main attributes used to characterize the monitoring protocols. Each attribute is defined using either continuous ranges of values (number of variables or series length) or discrete lists (period of data collection, resolution and spatial extension). Modified from Aspizua et al. (2014)

# 16.5 Spatial Organization of the Monitoring Programme

To study the potential effects of global change in a mountain range, we needed the sampling units to be spatially distributed according to the specific objectives of the programme and thus optimize and streamline the gathering of environmental information. First, we identified major environmental gradients over the entire mountain (e.g. elevation and exposure gradients). Then, the main ecosystem types along such gradients were identified, such as natural forests (Holm oak and Pyrenean oak forests [Quercus ilex and Q. pyrenaica], Scot pine forests [Pinus sylvestris var. nevadensis]), high-mountain shrublands (Juniperus communis), pine plantations, etc. These reference ecosystems, arranged over broad environmental gradients of elevation, exposure, and orientation, became the focus of ongoing sampling efforts. Then we installed some multiparametric meteo-stations to measure abiotic variables spatially associated with those reference ecosystems, together with ecological data. To increase the monitoring spatial resolution we installed wireless sensor networks around the meteo-station. These sensors collect abiotic data taking into account topographically controlled features (Scherrer and Körner 2010). In addition, several ecological protocols take data (demography, phenology, abundance of species, etc.) in each reference ecosystem (Aspizua et al. 2014). Finally, data from remote sensing (e.g. snow-cover-related indicators, vegetation indices, productivity) are gathered for the same reference ecosystem. Thus, we have developed the concept of Intensive Monitoring Stations (IMS) that denotes areas with a high density of ecological monitoring protocols coupled with abiotic measurements at several scales (Figs. 16.2 and 16.3).



**Fig. 16.2** Scheme of the Intensive Monitoring Stations. These are areas with high densities of ecological monitoring protocols located around a meteo-station. They also include a wireless sensor network to measure abiotic factors in selected microhabitats around the station (temperature, moisture, irradiance, etc.), as well as a phenocam. Modified from Zamora et al. (2016)



**Fig. 16.3** Spatial distribution of the Intensive Monitoring Stations (*dark-blue polygons*). *Blue line* corresponds to boundaries of Sierra Nevada Protected Area. Reprinted with the permission of Zamora et al. (2016)

Practical examples of use for this concentration of layers of ecological information taken at the same site and time are the following cases:

- 1. To establish robust spatiotemporal associations between variables that are closely related and that may depend each other, for example: (i) consumer/resource relations, such as fleshy fruit abundance and the corresponding abundance of frugivorous birds in the same plot, or flower and pollinator abundance; (ii) measurements of temperature and phenological responses of plants and animals associated on a per-plot basis; (iii) the relation between availability (dry and wet deposition) of aerosols collected by the sensors of the multiparametric tower and the in situ evaluation of processes of eutrophication in nearby aquatic and terrestrial systems; (iv) ground-based collection of photographs acquired from the same fixed location with phenocams for monitor phenological changes in vegetation status and environmental changes over long periods at the same site (Brown et al. 2016).
- 2. Comparison of data from sensors of a meteo-station with sensors placed in different microhabitats: on steep mountains slopes, the interplay between exposure and vegetation is leading to mosaics of life conditions. For example, the temperature experienced by an organism in a particular microhabitat can be totally different from the conditions measured by the nearest conventional meteo-station, depending on their aerodynamic coupling to the atmosphere. The more strongly an ecosystem is decoupled from atmospheric conditions by topography and vegetation structure, the more thermal microhabitat variation is observed (Scherrer and Körner 2010). Our Intensive Monitoring Station allows to analyse in real time the average atmospheric meteo-value (low spatial resolution), and the

- corresponding value for a number of microhabitats (high spatial resolution) found next to the meteo-station.
- 3. To validate reality-terrain: the great concentration of biophysical information gathered at the same plot of a reference ecosystem makes an IMS the ideal site for the necessary field validation required to interpret the spectral information acquired by remote sensing.

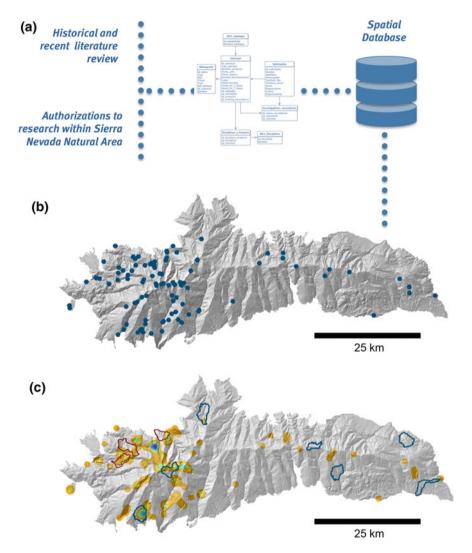
In short, we can consider an IMS as a monitoring hotspot, where heterogeneous data are collected at the same spatial location. The concentration of sampling points can be used to generate raster maps for IMS and thus layers of information can be spatially superimposed and analysed in GIS (Geographical Information System). Perhaps the most practical advantage of such an integrated approach is the cost savings associated with routine measurements to provide data for a wide variety of research purposes as well as for management. Our IMSs are a good example of multidisciplinary research to generate and apply scientific knowledge (Fahey et al. 2015).

## 16.6 Collection of Long-Term Data Series

The success of any global change programme depends on the quality of the data it collects, manages, and disseminates (Cook and Lineback 2008). Our monitoring programme aims to use information compiled in long-term research conducted in Sierra Nevada by naturalists and scientists belonging to different disciplines over the last several decades. We have collected information from several sources, such as reviews of historical literature published by naturalist scientists (up to 1960, see Titos-Martínez 2002; Ruano and Tinaut 2003; Garzón-Gutiérrez 2012); review of recent literature (after 1970); and information from the grey literature (project authorizations and research reports) related to the Sierra Nevada Protected Area. The aims of our recent literature review are (i) to gather all the scientific publications carried out in Sierra Nevada in the last 50 years; (ii) to identify the main research areas; and (iii) to geolocate the field sampling points. Our review in Web of Science (WoS) has resulted in a total of 1,038 publications related to the Sierra Nevada massif during the 1970-2015 period. The articles were distributed among 66 Web of Science categories. The five top-ranked research areas were "Ecology", "Plant Sciences", "Geosciences", "Environmental Sciences", and "Zoology". Using the information provided in each publication, we created a spatial database with the locations where the research was conducted. The preliminary results reveal that forests and aquatic systems (particularly alpine lakes) were the ecosystem types where more research was done.

We are also interested in compiling information on the current research being done in Sierra Nevada. Thus, we compiled information from research authorization documents for the Sierra Nevada Protected Area, from 2002 to 2015. Authorization documents contain basic information concerning the research activity, date, and location of the research area. After categorizing the raw information according to

several attributes (e.g. disciplines, spatial and temporal range, fauna/flora studied, etc.), we integrated it into a normalized and spatial database. Furthermore, we compiled basic metadata on the research projects conducted in Sierra Nevada over the last 15 years from the research projects database of the Spanish Network of National Parks. This approach has enabled us to characterize the main research topics as well as to identify and locate areas with a high concentration of research



**Fig. 16.4** Integration of the information from literature review and from recent (2002–2016) research activities conducted in Sierra Nevada into a spatial database (**a**). Spatial localization of the research activities in the past 15 years in Sierra Nevada (**b**). Map of density of research activities in Sierra Nevada (**c**) with an overlay of the location of the Intensive Monitoring Stations (*blue* and *red polygons*)

projects within Sierra Nevada (Fig. 16.4). Preliminary results have shown a spatial pattern with a high density of research activities at the western side of the mountain range (Fig. 16.4b). In particular, the areas with high densities of research projects correspond to high-mountain terrestrial and aquatic ecosystems, mountain rivers, and forests and shrublands. We also identified a lack of research activities in the central region of the range. The distribution of the research projects shows that the most arid ecosystems of Sierra Nevada (located on the eastern side) have scarcely been studied (Fig. 16.4c).

# 16.7 Data Management

An increasing demand for more detailed, high-quality data and information about natural resources and ecosystems functions requires trained personnel (resource specialist, data manager, researchers) working in collaboration to steward data and information assets (Cook and Lineback 2008). Information systems are fundamental for managing a large amount of data (Rüegg et al. 2014). Here, we distinguish two types of information: first, raw data collected directly in the field by scientific methods; second, structured information found in scientific papers and reports, slide presentations, videos, etc.

Raw data collected from the field is stored in relational spatial databases. To store processed information, we use relational databases that allow the fuzzy classification of the information into categories using the facilities of the web 2.0. For large amounts of information, it becomes critical to have a catalogue that highlights the main features of this information. This data about data is known as metadata or documentation. Metadata should answer prime questions about data, such as who created them, where they were collected, what method was used, and what organizational principle was used (Michener 2006). Metadata are very useful to share information between different information systems (Schildhauer et al. 2001).

Once an information system is established for the storage of documented data, the next step is to process and analyse raw data to provide information. From a functional and structural standpoint, an information system must be able to document and execute the algorithms that we use to process the data. Ideally, these tasks are run automatically using a scientific workflow software (Barseghian et al. 2010; McPhillips et al. 2009; Bonet et al. 2014). These tools allow the creation and execution of complex workflows by linking several computational steps (algorithms) in order to produce a given final product. Scientific workflow software can be used to run a spatial distribution model or even a simple query to a relational database. The results are also documented using the same standards described above.

We have developed an information system for the Sierra Nevada Global Change Observatory (Fig. 16.5). This system, called *Linaria* (https://linaria.obsnev.es—free access upon registration), acts as a repository storing raw data gathered by the monitoring programme as well as information generated through the processing of

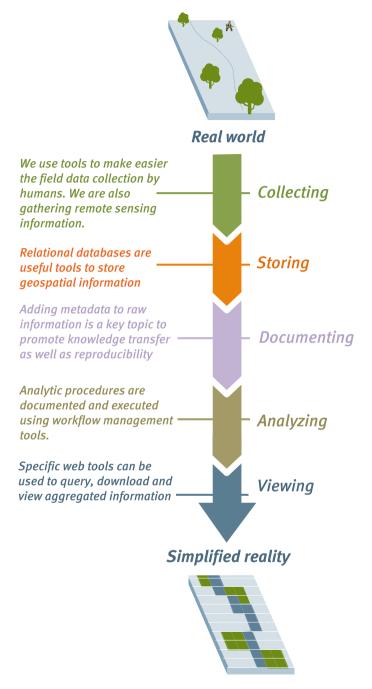


Fig. 16.5 Structure and main functionalities of the information system designed to store and analyse all the information gathered in the Sierra Nevada monitoring programme

such data. Data are stored in a standardized and documented way to facilitate its integration and analysis. Information generated is used in decision-aid tools and decision-making knowledge.

#### 16.8 Distillation of Information and Outreach

Effective science outreach and communication is critical if we are to improve environmental decision-making (Lubchenco 1998; Bennett et al. 2005). Data analysis, elaboration of scientific publications and distillation of the information is the crucial final stage of the information-management processes. A pillar of our monitoring programme is the collaboration with research experts trained for the work of analysing and interpreting the information gathered in the scientific context as well as the development of simulation models. As a result of the analysis and synthesis came scientific publications in peer-reviewed journals, followed by reports that distilled the results of the peer-reviewed publications for decision-makers (Driscoll et al. 2011; Zamora et al. 2016).

# 16.9 Detecting Changing Signals

In this section, we present a summary of the main results found at the site LTER of Sierra Nevada (Zamora et al. 2016). Specifically, we present a temporal evaluation of the two main drivers of global change: climate and land-use changes as well as the biotic and socioeconomic responses to these changes.

Apart from land-use and climate changes, other drivers of global change (Sala et al. 2000) appear to have a comparatively minor impact on Sierra Nevada. For instance, this massif is relatively far from centres of industrial activity and therefore anthropic pollution detected is low and comes mainly from the city of Granada (c. 235,000 inhabitants). On the contrary, Sierra Nevada is an invaluable watchtower to detect atmospheric depositions of remote origin. For example, for its geographic position in the extreme south of continental Europe, this massif receives aerosol depositions from the Sahara Desert (Morales-Baquero et al. 2006). Also, in Sierra Nevada National Park, no serious problems of invasive species have been detected yet, but other ecosystems situated at lower elevations are affected, especially aquatic ecosystems.

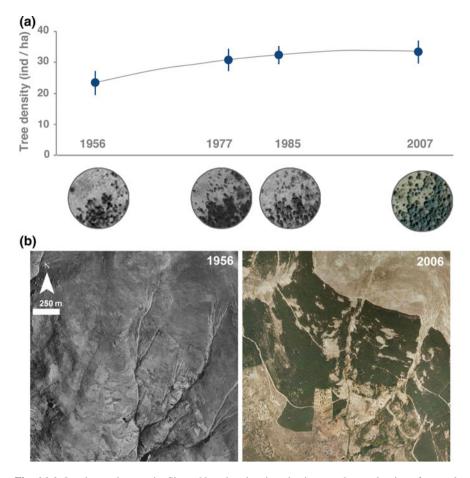
# 16.9.1 Land-Use Change

Land-use drive changes in the vegetation cover, affecting ultimately the biogeochemical and waters cycles, the stability of mountain slopes, and household economies. Centuries of human activity have changed the structure of the landscape in Sierra Nevada. Multiple pieces of evidence indicate that from about 3,000 years ago to the present, human activity intensified in Sierra Nevada (Anderson et al. 2011; Jiménez-Moreno and Anderson 2012; Jiménez-Moreno 2016). After 3000 BP the frequency of fires increased, and there are signs of grazing as well as mining; more recently, olive cultivation on a large scale at the lowest elevations together with pine reforestation have become characteristic.

The mountain landscapes of Sierra Nevada have undergone massive land-use changes from the past century. The sharp decline in agro-pastoral pressure due to rural depopulation raises major environmental and societal issues. For instance, there is evidence from paintings, forestry maps, and the land registry of the last 100 years (Jiménez-Olivencia et al. 2016; Moreno-Llorca et al. 2016) of a clear land-use shift over the last 50–60 years, due to both the abandonment of agricultural and livestock activities, as well as a surge in active reforestation (pine plantations; Fig. 16.6). Land-use change in the last 50 years has affected over half of the 170,000 ha of Sierra Nevada Protected Area.

We hypothesized that the land-use changes in Sierra Nevada should facilitate the native forest regeneration, and a process of colonization of marginal habitat (abandoned cropland, pine plantations) will occur. The distribution of the oak forests in Sierra Nevada and their degree of conservation are determined both by biophysical variables that are expressed at present (slope, climate, water availability, etc.), and by the dynamics of land-use changes in recent decades (intensive use and subsequent abandonment). We have quantified the ecological functions "seed production and dispersal" and "sapling survival and growth" both at the upper elevational limit as well in marginal habitats (i.e. abandoned croplands and pine plantations). The preliminary results showed that oak forests regenerated more readily on the north-eastern than on the southern slopes, whereas the colonization of abandoned crops seems to occur more intensely in the south than in the north-east (possibly due to the greater incidence of herbivory in the latter slope) (Pérez-Luque et al. 2015; Bonet et al. 2016).

Moreover, the ecosystem transformation associated with land-use changes drastically diminishes the biological legacies, including remnant native woody plants and their propagules. Consequently, the recuperation of community diversity within human-created habitats (such as abandoned cropland, pine plantations) depends heavily on both internal, in situ biological legacies, and external, well-conserved nearby areas, as a source of propagules. The effect of these historical and current ecological factors on current *Quercus* species regeneration under pine plantations has been analysed in Sierra Nevada massif (southern Spain). Our results indicate that native oak forest regeneration ability under pine plantations depends largely on land-use legacies, although nearby, well-conserved areas also provide propagules for colonization from outside the plantation (Gómez-Aparicio et al. 2009; Navarro-González et al. 2013; Pérez-Luque et al. 2016a). The higher the land-use intensity in the past, the weaker biological legacies are and, therefore, the weaker the current native forest regeneration ability, and vice versa.



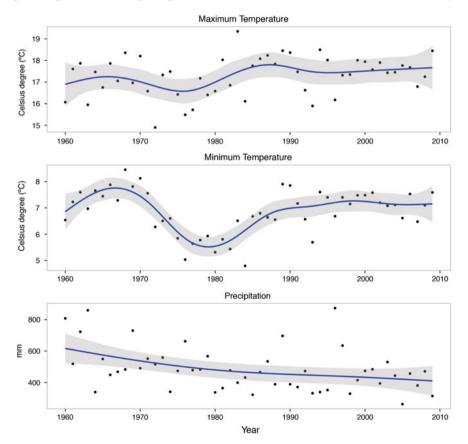
**Fig. 16.6** Land-use changes in Sierra Nevada, showing the increased tree density of natural Pyrenean oak forests (*Quercus pyrenaica*) in Sierra Nevada in the past 50 years (a). Comparative orthophotography showing the changes at the landscape level due to reforestation activities (pine plantations) (b)

Overall, our results suggest that *Quercus* forest regeneration responded more to changes in land use than to the rise in temperature (Pérez-Luque et al. 2015). Separating the respective effects of land use, climatic variability, and their interaction constitutes a major challenge but achievable only by experimental long-term approaches, and by repeated observations of more pristine areas (such as high mountains) from human impacts in order to establish a climate signal on the ecological processes. An understanding of the past and the present changes and subsequent impacts on mountain ecosystems of those major drivers and their interaction is a prerequisite for any management or adaptation strategy.

# 16.9.2 Climate Change

Rising temperatures and growing aridity become evident in the palaeolimnological indicators of the lakes of the Sierra Nevada (Anderson et al. 2011; Jiménez-Moreno and Anderson 2012). In addition, an increase in the chlorophyll-a content of these lakes over the last 120 years correlates well with temperature data for the corresponding period (Pérez-Martínez 2016). Overall, there has been progressive aridification over the last 7,000 years, with signs of a gradual increase in human activity for the last 3,000 years (Jiménez-Moreno 2016).

An analysis of the temporal pattern of the main climatic variables in Sierra Nevada for the last 50 years has revealed changes in annual temperatures (maximum and minimum) and rainfall (Fig. 16.7). Maximum and minimum temperatures have risen, especially after 1980s (Pérez-Luque et al. 2016b). This agrees with the general pattern of rising temperatures in the second half of the twentieth century



**Fig. 16.7** Time course of the annual maximum (*upper panel*) and minimum (*middle panel*) temperatures and annual rainfall (*lower panel*). Average values for all pixels (100 m pixel size) of Sierra Nevada are shown

observed at different scales on the Iberian Peninsula (Galán et al. 2001; De Castro et al. 2005). The precipitation shows a general decreasing pattern, being more pronounced in the western part than in the east. This pattern is consistent with the overall declining trend in the south of the Iberian Peninsula (Rodrigo et al. 1999; Ruiz-Sinoga et al. 2010).

All these changes in climate have implications for the dynamics of snow cover. Satellite information from MODIS (*Moderate Resolution Imaging Spectroradiometer*) for the period 2000–2014 have indicated a decrease in snow-cover duration over 79% of Sierra Nevada. There was a trend towards a delay in the date of the first snowfall and a trend towards earlier melting dates. The change has been more pronounced in magnitude at the summits than in the lowland areas (Bonet et al. 2016). For instance, above 3000 m a.s.l., the duration of snow cover decreased by an average of three days in the last 14 years. A significant recent decline in snow duration has also been reported from other mountain regions of Europe (Scherrer et al. 2004; Moreno-Rodríguez 2005; Marty 2008; Nikolova et al. 2013).

## 16.9.3 Biotic Responses to Land-Use and Climate Change

Mountain lakes as integrated ecological sensors

The combination of old studies and resampling of the same localities can help to integrate short-term data into long-term datasets (Müller et al. 2010). These long-term datasets can be used to evaluate spatiotemporal changes and trends in biological communities and their relation to drivers of global change, such as land use or climate in mountain regions. For example, an exhaustive review of the research on alpine lakes of Sierra Nevada from 1975 to the present has identified the role of these ecosystems as sentinels of change (Villar-Argaiz and Bullejos 2016; Medina-Sánchez et al. 2016). Unlike other European mountain lakes, the geographic location and geological history of Sierra Nevada cause high-mountain lakes to be exposed simultaneously to several environmental stressors: climatic anomalies (temperature and precipitation), UV radiation, aerosol deposition, and allochthonous nutrient input. High transparency, low nutrient content, and narrow temperature ranges found in high-mountain lakes qualifies them as sentinels of global change (Medina-Sánchez et al. 2016; Villar-Argaiz and Bullejos 2016). However, especially the great simplicity of their biological communities helps us to assess their impact on ecosystem functioning, as well as the evolution of organisms that inhabit them. Long-term monitoring of the population dynamics of pelagic plankton in the Laguna de la Caldera, the largest alpine lake of Sierra Nevada, indicates that phytoplankton has increased in parallel with the increase in the intensity and frequency of atmospheric aerosols (Villar-Argaiz and Bullejos 2016). These results suggest that allochthonous nutrients associated with Saharan intrusions have a fertilizing effect that stimulates the growth of algal biomass. These patterns are consistent with previous studies indicating that the Saharan depositions are important sources of nutrients, especially Phosphorus (Morales-Baquero et al. 2006), encouraging

primary productivity in the oligotrophic waters of mountain lakes of Sierra Nevada (Villar-Argaiz et al. 2001).

#### Elevation range extension

The consequences of climate and land-use changes are typically most evident in mountain habitats, where expansions or contractions in species' distribution ranges along elevation gradients may occur via the migration of species to new areas (Jump and Peñuelas 2005; Lenoir et al. 2008). Species may expand upwards into new areas that become favourable, and retract from those that turn unfavourable. For instance, a comparative study on macroinvertebrate communities in the rivers of Sierra Nevada in the 1980s and today reveals substantial changes (Sáinz-Bariáin et al. 2015). Some species in the 1980s that were associated with the middle elevation stretch of the rivers are today found in the higher reaches. As a result, the diversity of species in the upper reaches of rivers is far greater than 30 years ago. In places where the water temperature has increased more, there has also been a major increase in the diversity of caddisflies. In the case of Plecoptera, it has been found that the lower limits of the distribution of some species have contracted, while the distribution at the upper limits has remain unchanged.

In terrestrial ecosystems a similar pattern has been found. Faunistic inventories conducted 20–40 years ago have been repeated in recent years. Significant changes in the spatial distribution and/or abundance of several groups of species were found. For insects, an elevational migration has been confirmed for dung beetles (Menéndez et al. 2014). The results show that within 25 years, 89% of the species increased their average elevation and upper distribution limits while more than 84% increased their lower distribution limits. The average elevational ascent of dung beetles in Sierra Nevada over 25 years was 400 m, coinciding with a rise of the same magnitude in the butterfly Apollo (Barea-Azcón 2016). Meanwhile, ants (Formicidae, Hymenoptera) have also risen in elevation, at least in the case of two species (*Proformica longiseta* and *Formica fusca/lemani*), which have expanded their upper distribution limits by about 200 m on the southern slopes of Sierra Nevada (González-Megías et al. 2016).

Among vertebrates, equivalent responses have also been found. For instance, passerines have shown marked temporal dynamics over the last 30 years which have been strongly influenced by global change (Zamora and Barea-Azcón 2015). Some generalist mountain species are now more abundant than before in high-mountain areas, while the most typical alpine species have become progressively scarcer. Overall, there has been a decline in montane species, which have been replaced by more thermophilic Mediterranean lowland species. We conclude that, within the global change context, protected mountain areas play a vital role in maintaining biodiversity, as populations can adapt to shifting conditions, moving along elevation gradients, according to their ecological requirements.

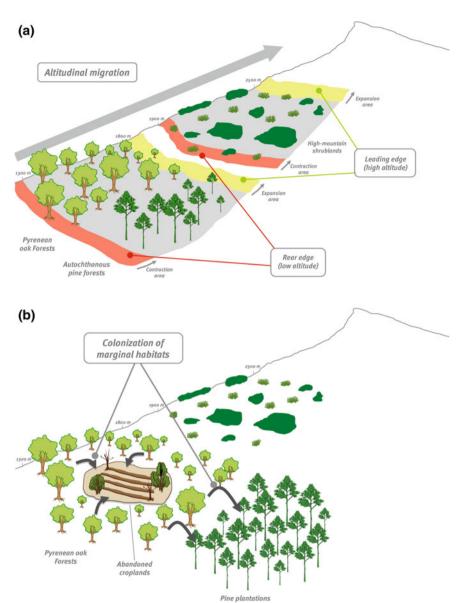
Ongoing changes in climate are altering ecological conditions for many plant species, and are most evident at the edge of the geographical distribution of a species, where range expansions or contractions may occur. For example, the demographic structure of both *Pinus sylvestris* and *Juniperus communis* 

populations differs across the elevational distribution in Sierra Nevada, where low-elevation populations of *P. sylvestris* and *J. communis* are susceptible to decline through reduced growth, seed production, and population regeneration (García et al. 2000; Matías and Jump 2015). Both species presented a significantly reduced proportion of young individuals at the lowermost populations, and a clear dominance of older age classes (Matías and Jump 2015; Rabasa et al. 2013; Benavides et al. 2013; 2015). This contrasts sharply with the pattern found at the treeline, where a higher proportion of saplings appeared and an even distribution was found across age classes. These results indicate an ongoing elevational displacement for both species at the southernmost edge of the geographical distribution area (Fig. 16.8a). Still, evidence for lowland contractions in these woody species is scarce due to generally great individual longevity and relatively slow decline until survival thresholds are exceeded, especially for slow-growing species such as *J. communis* (García and Zamora 2003).

However, factors other than climate affect species growth and reproduction at the same time such as land-use change and herbivory pressure (Zamora et al. 2001; Zamora and Matías 2014; Herrero et al. 2012, 2016), and the result of their interactions are strongly heterogeneous across areas and species. Therefore, research across altitudinal gradients taking into account other factors in addition to climate, such as biotic interactions (mostly herbivory), land use, or local adaptations, are strongly recommended for an accurate forecasting of climate-change consequences on long-lived woody plant species.

Summit vegetation also showed signals of change, with an expansion of some species, and greater vegetation cover. Many alpine plants have become rarer in the period 2001–2008 on the high mountains of the European continent, whereas plants from low elevations become more common (Gottfried et al. 2012). In Sierra Nevada, over the last 11 years, 13 alpine species have disappeared from monitoring plots and, at the same time, five new taxa have appeared (Gottfried et al. 2012; Sánchez-Rojas and Molero Mesa 2016).

Overall, these results for plant and animal species show that a high mountain, such as Sierra Nevada, plays a vital role in maintaining biodiversity in the context of global change. Species populations can adapt to climatic changes elevationally by moving according to their ecological necessities, although plants and animals do not necessarily need to climb several hundred metres in elevation to find suitable new habitats in case of warming but may find conditions matching their "thermal niche" over very short distances, taking advantage of the mosaics of microhabitats characterizing mountains slopes (Scherrer and Koerner 2011). These results indicate that montane ecological communities that are considered rather stable are, in fact, undergoing strong spatial and temporal dynamics because of climate warming (and more so after land-use change). As a result, there is a convergence in biotic responses to these two major drivers of global change (land-use and climatic changes), threatening high-mountain species while at the same time opening opportunities for species from lower elevations. All of this seems to be restricting the distribution range or leading to the extinction of rare, endemic, and/or specialist species, parallel to expansions in the distribution range of generalist species. This may be increasing



**Fig. 16.8** An elevational displacement has been observed for major woody plant species (Pyrenean oak, autochthonous pine and high-mountain shrublands) (a). We also found an outstanding woodland expansion towards marginal areas (abandoned croplands and pine plantations) (b). Modified from Pérez-Luque et al. (2015)

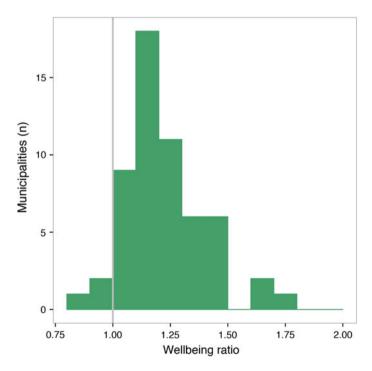
the similarity of taxonomic composition among communities along elevation gradients. This process can be envisaged as the first stage of a taxonomic homogenization processes (McKinney and Lockwood 1999; Olden and Rooney 2006) or, in

other words, a temporal decline in beta diversity. To determine to what degree the mosaic of ecological conditions favoured by the topography of mountains delays (or even halts), this widespread process of biotic homogenization (i.e. favouring beta diversity) is a highly relevant topic for scientific investigation of the future.

The maintenance of the monitoring programme and associated research is crucial to test whether these changes in the composition, abundance and altitudinal distribution, will have consequences in the organization of food webs and in ecosystem functioning, as has already been demonstrated for high-mountain lakes (Medina-Sanchez et al. 2004).

## 16.9.4 Socioeconomic Responses to Global Change

Changes in land use and climate have direct consequences for human populations and socioeconomic activities. The organization of the mountain economy in Sierra Nevada has drastically changed during the last 60 years. The rural exodus and the decline in traditional land-use practices, mainly agriculture and livestock husbandry, together with re-afforestation, have contributed to a general expansion of forested areas. Today, a socioeconomic analysis must consider different perspectives, ecosystem services, and their multiple uses.



**Fig. 16.9** Well-being ratio for the municipalities of Sierra Nevada. Municipalities to the *right* of the *vertical* line represent those that have improved their welfare in the past 20 years

Mountains are sources of multiple ecosystem services, benefiting the welfare of human populations. We performed a temporal analysis of the well-being in the municipalities of the Sierra Nevada mountain range, comparing the welfare at two points in time: before the declaration of the protected area (20 years ago) and at the present. For this, we used data from 22 socioeconomic indicators belonging to eight dimensions of well-being according to Millennium Ecosystem Assessment. For each municipality we computed a synthetic indicator of well-being, using an approach based on compound weighted indices (Bonet et al. 2015). The index shows a significant increase in well-being for 94% of the municipalities analysed (Fig. 16.9). These results agree with those found for an analysis performed at the regional scale, where the increment in well-being was higher for municipalities in protected areas than outside of them (Bonet-García et al. 2015). This indicates that protected areas, in addition to acting as instruments for the conservation of biodiversity and ecological processes, generate ecosystem services valuables for human populations.

## 16.10 From Monitoring to Action in a Changing World

# 16.10.1 Cross-Scale Interaction: Think Globally, Act Locally

Long-term monitoring, data analysis, and policy-making can be put into practice at different spatial scales. Cross-scale interactions arise when the driver and response variables in cause–effect relationships operate at different spatial and temporal scales (Soranno et al. 2014). Understanding these spatial and temporal scales requires the creation of a "network of networks" (Peters et al. 2008) for observation, experimentation, modelling, and policy-making. Thus, we have devoted effort to establishing links between our monitoring programme and other similar initiatives. First, Sierra Nevada is part of the Spanish LTER (Long-Term Ecological Research) network (http://www.lter-spain.net). This network provides access to analytical tools, harmonized protocols, ecoinformatics procedures to manage the information and it is also a network of networks working on ecological monitoring. Moreover, our site is connected to regional (Andalusian Network of Global Change Observatories) as well as national (Monitoring Global Change in National Parks) initiatives that share this long-term philosophy. Finally, our site has participated in several EU projects such as eLTER (H2020 project aiming to vertebrate the European LTER network http://www.lter-europe.net/projects/eLTER), ECOPOTENTIAL (H2020 project aiming to quantify ecosystem services using remote sensing http://www. ecopotential-project.eu/), and ADAPTAMED (Life project) aiming to implement real managerial activities to improve resilience in Sierra Nevada ecosystems.

# 16.10.2 The Application of Monitoring Information to Adaptive Management

Long-term observations are critical for making informed decisions in many environmental management contexts. For example, long-term studies can be important in quantifying the effectiveness of conservation management activities such as ecosystem restoration, where prolonged periods might be required for systems to recover following major human disturbance. As opposed to the traditional management characterized by a lack of monitoring, we have opted for "adaptive management" based on follow-up of actions in order to evaluate the effects of a treatment submitted to testing. We have put into practice this philosophy in Sierra Nevada, proposing key questions from the outset, defining the goals to be pursued with the actions undertaken, and specifying the methodological and analytical details necessary to address these efforts.

In this sense, several projects are already under way, such as actions for the naturalization of pine reforestation, monitoring of the effectiveness of post-fire restoration actions, and analysis of the population dynamics of pine processionary moth *Thaumetopoea pityocampa* (see Chap. 8 in Zamora et al. 2016). We are also collaborating in a LIFE project called ADAPTAMED (protection of key ecosystem services threatened by climate change through adaptive management of Mediterranean socioecological systems), led by the Environmental Ministry of the Regional Government of Andalusia. The project focuses on implementing, monitoring, evaluating, and disseminating adaptive management measures, with an ecosystem approach. The project objectives aim to reduce the negative impact of climatic change in the area of influence of Natural Protected Areas. As a result, an increase in the resilience of the socio-ecosystems concerned is expected, in such a way that their future provision of services will also be improved, in comparison to the scenario of no intervention.

# 16.10.3 Last, But not the Least: Maintaining Monitoring Over the Long Term

Global change monitoring programmes arise from the visionary effort of some people, but must survive those founding individuals with the challenge to survive the year-to-year political vagaries through consolidation of monitoring programmes into the existing research institutions (Universities, National Research Agencies) and environmental management institutions (public authorities responsible for environmental management). Research institutions have to vertebrate short-term research ordinarily engaged by individual researchers into long-term research and monitoring programme to ensure the continuity for collecting, documenting,

and analysing key biophysical and socioeconomic processes. For understanding, modelling, and managing nature, nothing has more value than a long series of field data. To amass this long series of data and maintain it live and operative over time, long-term needs financial and personal resources that are not always available for planning failures. Meanwhile, the use of monitoring information will allow managers to confront and mitigate global change threats to ecosystem function and services by designing the appropriate management measures. If the project is a conscientious, forthright initiative, the continuity of the monitoring programme must necessarily be guaranteed by the above-mentioned institutions, and must be coordinated with the other nodes forming a network of observatories in order to make the diagnosis and forecast of the health of the planet.

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