Networks, Centers, Observatories, and Field Stations

Global Change Impact in the Sierra Nevada Long-Term Ecological Research Site (Southern Spain)

Regino Zamora,[1,2] Antonio J. Pérez-Luque,[1,2] Francisco J. Bonet,[1,2] José Miguel Barea-Azcón,[3] Rut Aspizua,[3] Francisco J. Sánchez-Gutiérrez,[4] Francisco J. Cano-Manuel,[4] Blanca Ramos-Losada,[4] and Ignacio Henares-Civantos[4]

[1]Department of Ecology, Faculty of Sciences, University of Granada, Avda. Fuentenueva s/n, Granada 18071 Granada, Spain
[2]Laboratory of Ecology (iEcolab), Andalusian Institute for Earth System Research, University of Granada, Avda. del Mediterráneo s/n, Granada 18006 Granada, Spain
[3]Agencia de Medio Ambiente y Agua, Regional Ministry of the Environment and Land Management, Junta de Andalucía, C/Minerva 7 Edificio Zeus III, Granada 18014 Spain
[4]Sierra Nevada National Park, Nature Park and Biosphere Reserve, Regional Ministry of the Environment and Land Management, Junta de Andalucía, Carretera Antigua de Sierra Nevada km. 7, Pinos Genil 18191 Granada, Spain

Long-term Ecological Research (LTER) provides useful information to understand the complex dynamics of natural systems (Müller et al. 2010, Lindenmayer et al. 2012). This is especially relevant in mountain regions that show strong gradients of environmental conditions (Scherrer and Körner 2010). The high sensitivity and vulnerability of mountain ecosystems provide unique opportunities to detect and analyze global change in ecological processes as well as their effects on the socioeconomic conditions of these areas (Beniston 2003, Huber et al. 2005).

Sierra Nevada, a high mountain range located in southern Europe (Fig. 1), represents an exceptional ecology laboratory of field conditions, offering the advantage of the vast mosaic of ecological conditions existing throughout the complex relief. In this Mediterranean mountain region, a long-term monitoring program was established 9 years ago to assess the impact of global change on the ecosystems of this area. This long-term research project, called *Sierra Nevada Global Change Observatory* (OBSNEV),

Box 1. Sierra Nevada

Sierra Nevada (Andalusia, SE Spain; Fig. 1) is a mountainous region covering more than 2,000 km^2 with an elevation range of between 860 m and 3,482 m a.s.l. It is considered one of the most important biodiversity hotspots in the Mediterranean region (Blanca et al. 1998), hosting 105 endemic plant species for a total of 2,353 taxa of vascular plants (33% and 20% of Spanish and European flora, respectively; Lorite 2016). Sierra Nevada receives legal protection in multiple ways, having been declared: a MAB Biosphere Reserve, Special Area of Conservation (Natura 2000 network); Natural Park and National Park; and Important Bird Area. Furthermore, Sierra Nevada is included in the World Green List of Protected Areas (IUCN) and forms part of the Spanish LTER network. The main economic activities in this mountain region are agriculture, tourism, livestock raising, beekeeping, mining, and skiing (Bonet et al. 2010).

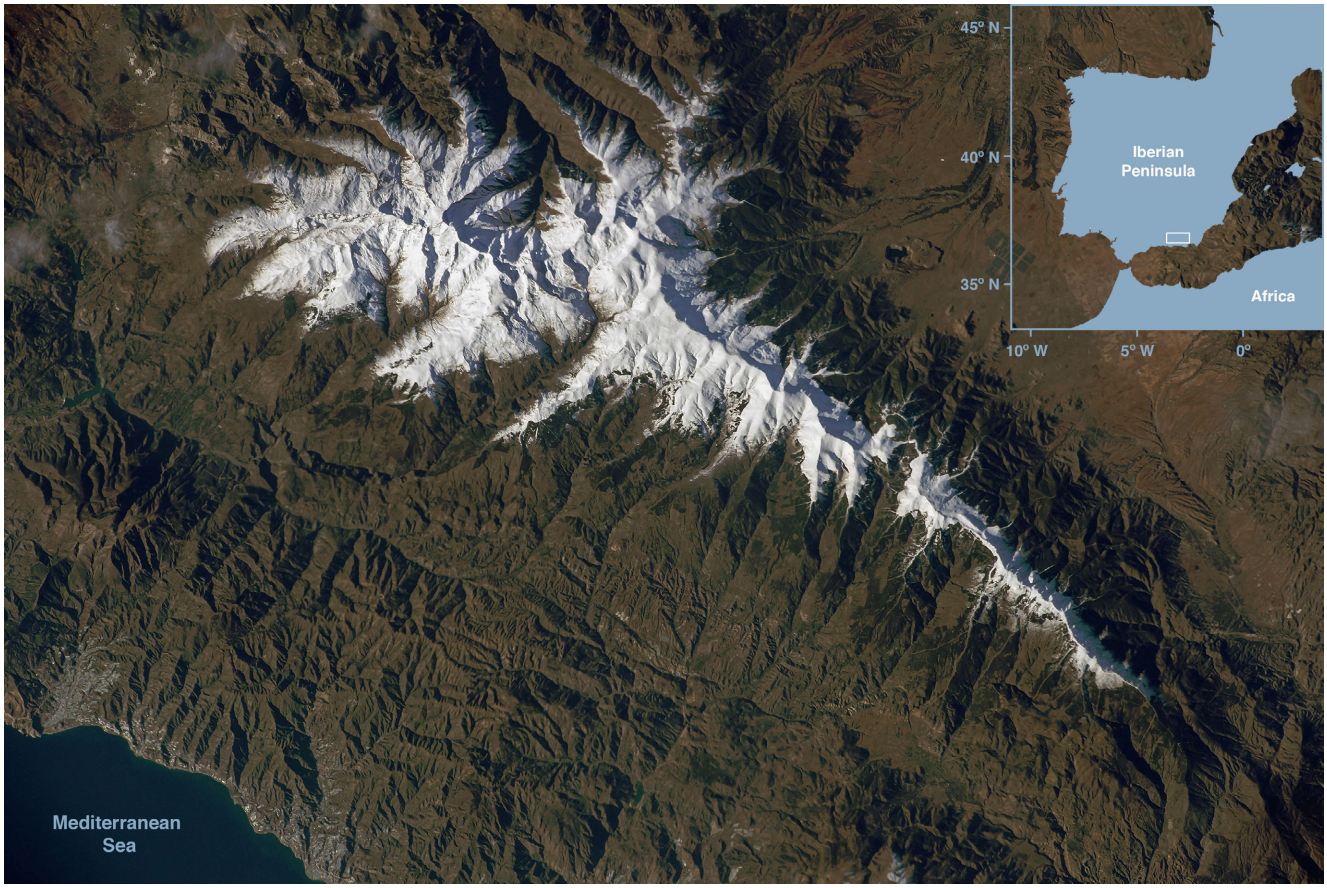

Fig. 1. Location (top-right) and remote view of Sierra Nevada mountain region (image from the International Space Station taken in December 2014; courtesy of "Earth Science and Remote Sensing Unit, NASA Johnson Space Center").

was conceived to bring together useful and relevant information regarding the far-reaching effects of global change on ecological systems and the socioeconomics of Sierra Nevada (Aspizua et al. 2010, Bonet et al. 2011).

Global change impact in Sierra Nevada: objectives and methodologies

The design of the OBSNEV monitoring program was inspired by the conceptual framework of Global Change in Mountain Regions (Grabherr et al. 2005). Our monitoring program is based on specific questions concerning the global change impact, the functioning of the natural systems, and their foreseeable responses under the new scenarios of change (Lindenmayer and Likens 2009). The monitoring methodologies were defined to evaluate both the state of the key ecological functions as well as the structure of the main ecosystems in Sierra Nevada and the possible impact of global change on this massif. The OBSNEV project has four cornerstones: a monitoring program that collects information on biophysical variables (Aspizua et al. 2014); an information system to store and manage all the information gathered (http://obsnev.es/linaria.html; free access upon registration); a plan to promote adaptive management of natural resources; and an outreach program to disseminate all the available information to potential users.

The OBSNEV project is linked to other national and international monitoring networks: LTER-Spain, ILTER (International Long-term Ecological Research), Global Change in Mountain Sites, etc. This project is also involved in several European projects such as ECOPOTENTIAL (H2020 project www.ecopotential-project.eu/), EU BON (http://eubon.eu/), eLTER (H2020 project www.lter-europe.net/projects/eLTER), and ADAPTAMED (Life Programme).

Several reports have been released from the outset of the monitoring in Sierra Nevada LTER site (Fig. 2). First, we identified the potential impact of global change on the main ecosystems of Sierra Nevada and the ecosystem services affected (Bonet et al. 2010; http://sl.ugr.es/structure_obsnev_en).

Fig. 2. Time course of the main reports generated by the OBSNEV from its starting point in 2007. The first report set the structure and data basic of the project (http://sl.ugr.es/structure_obsnev_en). A second report was published with the monitoring methodologies (http://sl.ugr.es/methods_obsnev_en), and finally, a report was filed on the impact of the global change in the Sierra Nevada ecosystems (http://sl.ugr.es/results_obsnev_en).

Then, we defined standardized methodological protocols to measure that impact (Aspizua et al. 2014; http://sl.ugr.es/methods_obsnev_en). After 9 years of the implementation of the OBSNEV, an initial diagnosis of the global change impact on the ecosystems of Sierra Nevada has been published (Zamora et al. 2016; http://sl.ugr.es/results_obsnev_en). To prepare this last report, we have used information from several sources. Apart from the data generated by the OBSNEV monitoring program (more than 100 variables of 48 different methodologies; Aspizua et al. 2014), we compiled information from several research groups that have been working for decades in this mountain region. Additionally, reviews of historical literature (published by naturalists up to 1960) were made, together with reviews of more recent scientific literature. Furthermore, we compiled basic metadata and data of the research activities and projects conducted in Sierra Nevada protected area over the last 15 years.

Global change impact in Sierra Nevada: initial results

We have identified the main aspects of global change impact and have analyzed the biophysical and socioeconomic data available to assess exposure, sensitivity, and adaptive capacity of Sierra Nevada ecosystems to future scenarios. A report with information concerning this impact in this mountain range has recently been published (Zamora et al. 2016, http://sl.ugr.es/results_obsnev_en). To generate this report, we used information as mentioned above.

A highlight of this report is its multidisciplinary nature, with the participation of 69 authors from different scientific disciplines belonging to 11 national and international institutions. The results are clustered in 10 chapters covering the main drivers of the global change: climate and land-use change, and also the effects of these changes on the snow cover dynamics and on the functioning and structure of the main terrestrial and aquatic ecosystems of this mountain region (Fig. 3).

Climate change is evident in this mountain region. A rise in temperatures and a progressive aridification have been reported from paleolimnological indicators of the lakes of Sierra Nevada corresponding to the last 7,000 years (Jiménez-Moreno and Anderson 2012, Jiménez-Moreno 2016). The temporal pattern of the main climatic variables for the massif revealed higher maximum and minimum temperatures as well as a lower annual precipitation. These results are consistent with the pattern discerned in the southern part of Iberian Peninsula (Rodrigo et al. 1999, de Castro et al. 2005). All these climatic changes could have wielded an impact in the dynamics of snow cover. In fact, a reduction in the snow cover duration from the period 2000–2014 has been recorded (Bonet et al. 2016, Pérez-Luque et al. 2016).

From about 3,000 years ago to the present, human activity intensified in the Sierra Nevada with an increase in olive cultivations and pine plantations and more frequency of fires, among other trends (Anderson et al. 2011, Jiménez-Moreno and Anderson 2012, Jiménez-Moreno 2016). In the last 50 years, the mountains landscapes of Sierra Nevada have undergone massive land-use changes, affecting over half of the 170,000 ha of the Sierra Nevada protected area (Jiménez-Olivencia et al. 2016).

All these changes have directly influenced ecosystem processes and structure. The high-mountain lakes of Sierra Nevada have undergone significant changes in their ecological processes (Villar-Argaiz et al. 2001, Morales-Baquero et al. 2006, Medina-Sánchez et al. 2016, Villar-Argaiz and Bullejos 2016). Range expansion and elevational shifts have been recorded for several taxonomical groups. Macroinvertebrate community of the upper reaches of rivers currently hosts more species diversity than 30 years

Fig. 3. Impact of the global change has been reported for terrestrial and aquatic ecosystems of the Sierra Nevada. (a) natural forests (Pyrenean [*Quercus pyrenaica*] and Holm oak [*Quercus ilex*]) with pine plantations. (b) Summit environments with Alpine lakes and high-mountain meadows are some of the main ecosystems studied. Photo credits: Antonio J. Pérez-Luque (top) and Ernesto Sofós-Navero (bottom).

ago (Sáinz-Bariáin et al. 2015). For terrestrial ecosystems, similar patterns have been found, with significant changes in the spatial distribution and/or abundance of some groups of vertebrates (Zamora and Barea-Azcón 2015) as well as certain invertebrates, such as dung beetles (Menéndez et al. 2014), butterflies (Barea-Azcón 2016), and ants (González-Megías et al. 2016).

Changes in land use and climate also had direct consequences for human populations and socioeconomic activities, as the mountain economy in the Sierra Nevada has drastically changed during the last decades (Bonet-García et al. 2015).

In short, the LTER site in Sierra Nevada has compiled an enormous amount of environmental information and mobilized the scientific community working in Sierra Nevada to create a long-term research infrastructure. This project has also demonstrated its ability to establish linkages with similar projects at national and international scales. Furthermore, the foundations have been laid for effectively transferring these results to the management level. The continuation of this work requires evolution from the project stage to being considered as a long-term infrastructure, with the support and commitment of the public administrations and academic institutions involved.

References

Anderson, R. S., G. Jiménez-Moreno, J. S. Carrión, and C. Pérez-Martínez. 2011. Postglacial history of alpine vegetation, fire, and climate from Laguna de Río Seco, Sierra Nevada, southern Spain. Quaternary Science Reviews 30:1615–1629.

Aspizua, R., F. J. Bonet, R. Zamora, F. J. Sánchez-Gutiérrez, F. J. Cano-Manuel, and I. Henares-Civantos. 2010. El observatorio de cambio global de Sierra Nevada: hacia la gestión adaptativa de los espacios naturales. Ecosistemas 19:56–68.

Aspizua, R., J. M. Barea-Azcón, F. J. Bonet, A. J. Pérez-Luque, and R. Zamora, editors. 2014. Sierra Nevada Global-Change Observatory. Monitoring methodologies. Consejería de Medio Ambiente, Junta de Andalucía. http://sl.ugr.es/methods_obsnev_en

Barea-Azcón, J. M. 2016. The phenology of butterflies in Sierra Nevada. Pages 133–137 *in* R. Zamora, A. J. Pérez-Luque, F. J. Bonet, J. M. Barea-Azcón, and R. Aspizua, editors. Global change impacts in Sierra Nevada: challenges for conservation. Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía, Granada, Spain.

Beniston, M. 2003. Climatic change in mountain regions: a review of possible impacts. Climatic Change 59:5–31.

Blanca, G., M. Cueto, M. J. Martínez-Lirola, and J. Molero-Mesa. 1998. Threatened vascular flora of Sierra Nevada (Southern Spain). Biological Conservation 85:269–285.

Bonet, F. J., A. J. Pérez-Luque, R. Moreno, and R. Zamora. 2010. Sierra Nevada global change observatory. Structure and basic data. Consejería de Medio Ambiente, Junta de Andalucía. http://sl.ugr.es/structure_obsnev_en

Bonet, F. J., A. J. Pérez-Luque, and R. Perez-Perez. 2016. Trend analysis (2000–2014) of the snow cover by satellite (MODIS sensor). Pages 43–46 *in* R. Zamora, A. J. Pérez-Luque, F. J. Bonet, J. M. Barea-Azcón, and R. Aspizua, editors. Global change impacts in Sierra Nevada: challenges for conservation. Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía, Granada, Spain.

Bonet, F. J., R. Aspizua Cantón, R. Zamora, F. J. Sánchez Gutiérrez, F. J. Cano-Manuel León, and I. Henares-Civantos. 2011. Sierra Nevada Observatory for monitoring global change: towards the adaptive management of natural resources. Pages 48–52 *in* Austrian MaB Committee, editor. Biosphere reserves in the Mountains of the world Austrian. Excellence in the clouds? Austrian Academy of Science Press, Vienna, Austria.

Bonet-García, F. J., A. J. Pérez-Luque, R. A. Moreno-Llorca, R. Perez-Perez, C. Puerta-Piñero, and R. Zamora. 2015. Protected areas as elicitors of human well-being in a developed region: a new synthetic (socioeconomic) approach. Biological Conservation 187:221–229.

de Castro, M., J. Martí-Vide, and S. Alonso. 2005. El clima de España: pasado, presente y escenarios de clima para el siglo XXI. Pages 1–64 *in* J. Moreno-Rodríguez, editor. Evaluación preliminar de los impactos en España por efecto del cambio climático. rincipales conclusiones de la evaluación preliminar de los impactos en España por efecto del cambio climático. Ministerio de Medio Ambiente, Madrid, Spain.

González-Megías, A., R. Menéndez, and A. Tinaut. 2016. Shifts in the elevational ranges of insects in Sierra Nevada: evidence of climate change. Pages 120–122 *in* R. Zamora, A. J. Pérez-Luque, F. J. Bonet, J. M. Barea-Azcón, and R. Aspizua, editors. Global change impacts in Sierra Nevada: challenges for conservation. Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía, Granada, Spain.

Grabherr, G., A. Björnsen Gurung, J.-P. Dedieu, W. Haeberli, D. Hohenwallner, A. F. Lotter, L. Nagy, H. Pauli, and R. Psenner. 2005. Long-term environmental observations in mountain biosphere reserves: recommendations From the EU GLOCHAMORE Project. Mountain Research and Development 25:376–382.

Huber, U. M., H. Bugmann, and M. A. Reasoner, editors. 2005. Global change and mountain regions: an overview of current knowledge. Springer, New York, New York, USA.

Jiménez-Moreno, G. 2016. Reconstruction of the vegetation from palynological analysis. Pages 50–52 *in* R. Zamora, A. J. Pérez-Luque, F. J. Bonet, J. M. Barea-Azcón, and R. Aspizua, editors. Global change impacts in Sierra Nevada: challenges for conservation. Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía, Granada, Spain.

Jiménez-Moreno, G., and R. S. Anderson. 2012. Holocene vegetation and climate change recorded in alpine bog sediments from the Borreguiles de la Virgen, Sierra Nevada, southern Spain. Quaternary Research 77:44–53.

Jiménez-Olivencia, Y., L. Porcel-Rodríguez, A. Caballero-Calvo, and F. J. Bonet. 2016. Land-use changes in Sierra Nevada over the last 50 years. Pages 56–58 *in* R. Zamora, A. J. Pérez-Luque, F. J. Bonet, J. M. Barea-Azcón, and R. Aspizua, editors. Global change Impacts in Sierra Nevada: challenges for conservation. Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía, Granada, Spain.

Lindenmayer, D. B., and G. E. Likens. 2009. Adaptive monitoring: a new paradigm for long-term research and monitoring. Trends in Ecology & Evolution 24:482–486.

Lindenmayer, D. B., et al. 2012. Value of long-term ecological studies. Austral Ecology 37:745–757.

Lorite, J. 2016. An updated checklist of the vascular flora of Sierra Nevada (SE Spain). Phytotaxa 261:1–57.

Medina-Sánchez, J. M., J. A. Delgado-Molina, and P. Carrillo. 2016. Sentinels of global change (I): mixotrophic algae in La Caldera Lake. Pages 83–85 *in* R. Zamora, A. J. Pérez-Luque, F. J. Bonet, J. M. Barea-Azcón, and R. Aspizua, editors. Global change impacts in Sierra Nevada: challenges for conservation. Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía, Granada, Spain.

Menéndez, R., A. González-Megías, P. Jay-Robert, and R. Marquéz-Ferrando. 2014. Climate change and elevational range shifts: evidence from dung beetles in two European mountain ranges. Global Ecology and Biogeography 23:646–657.

Morales-Baquero, R., E. Pulido-Villena, and I. Reche. 2006. Atmospheric inputs of phosphorus and nitrogen to the southwest Mediterranean region: biogeochemical responses of high mountain lakes. Limnology and Oceanography 51:830–837.

Müller, F., C. Baessler, H. Schubert, and S. Klotz, editors. 2010. Long-term Ecological Research. Between theory and application. Springer, Nueva York, New York, USA.

Pérez-Luque, A. J., J. Herrero, F. J. Bonet, and R. Pérez-Pérez. 2016. Temporal trend of the snow-related variables in Sierra Nevada in the last years: an analysis combining Earth Observation and hydrological modelling. Geophysical Research Abstracts Vol. 18, EGU2016-16526.

Rodrigo, F. S., M. J. Esteban-Parra, D. Pozo-Vázquez, and Y. Castro-Díez. 1999. A 500-year precipitation record in Southern Spain. International Journal of Climatology 19:1233–1253.

Sáinz-Bariáin, M., C. Zamora-Muñoz, J. J. Soler, N. Bonada, C. E. Sáinz-Cantero, and J. Alba-Tercedor. 2015. Changes in Mediterranean high mountain Trichoptera communities after a 20-year period. Aquatic Sciences 78:669–682.

Scherrer, D., and C. Körner. 2010. Infra-red thermometry of alpine landscapes challenges climatic warming projections. Global Change Biology 16:2602–2613.

Villar-Argaiz, M., and F. J. Bullejos. 2016. Sentinels of global change (II): herbivorous consumers in La Caldera Lake. Pages 86–91 *in* R. Zamora, A. J. Pérez-Luque, F. J. Bonet, J. M. Barea-Azcón, and R. Aspizua, editors. Global change impacts in Sierra Nevada: challenges for conservation. Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía, Granada, Spain.

Villar-Argaiz, M., J. M. Medina-Sánchez, L. Cruz-Pizarro, and P. Carrillo. 2001. Inter- and intra-annual variability in the phytoplankton community of a high mountain lake: the influence of external (atmospheric) and internal (recycled) sources of phosphorus. Freshwater Biology 46:1017–1034.

Zamora, R., and J. M. Barea-Azcón. 2015. Long-term changes in mountain passerine bird communities in the Sierra Nevada (Southern Spain): a 30-year case study. Ardeola 62:3–18.

Zamora, R., A. J. Pérez-Luque, F. J. Bonet, J. M. Barea-Azcón, and R. Aspizua, editors. 2016. Global change impacts in Sierra Nevada: challenges for conservation. Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía, Granada, Spain. http://sl.ugr.es/results_obsnev_en