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Sierra Nevada

Global Change Impacts in Sierra Nevada:
Challenges for Conservation

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CONSEJERÍA DE MEDIO AMBIENTE Y ORDENACIÓN DEL TERRITORIO

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Technical coordinators: Fco. Javier Sánchez Gutiérrez, Ignacio Henares Civantos, Blanca Ramos Losada and Fco. Javier Cano-Manuel León.
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Fundación Biodiversidad

eug EDITORIAL UNIVERSIDAD DE GRANADA

Contributors

Domingo Alcaraz Segura
dalcaraz@ugr.es
Departamento de Botánica, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España
-
Departamento de Biología y Geología
Centro Andaluz para la Evaluación y Seguimiento del Cambio Global
Universidad de Almería
Ctra. Sacramento s/n. 04120 La Cañada de San Urbano (Almería), España

José Antonio Algarra Ávila
jalgarra@agenciamedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

Rut Aspizua Cantón
rut.aspizua.ext@juntadeandalucia.es
Agencia de Medio Ambiente y Agua de Andalucía.
Área de Conservación, Espacio Natural de Sierra Nevada
Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía
Carretera Antigua de Sierra Nevada, Km 7. 18191 Pinos Genil (Granada), España
-
raspizua@agenciamedioambienteyagua.es
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

José Miguel Azañón Hernández
jazanon@ugr.es
Departamento de Geodinámica, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Elena Ballesteros Duperón
eballesterosd@agenciademedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

José Miguel Barea Azcón
jbarea@agenciamedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

Maribel Benítez Lechuga
mbenitez@ugr.es
Departamento de Zoología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Cristina Bollullos Sánchez
cbollullos@agenciamedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

Francisco Javier Bonet García
fjbonet@ugr.es
Laboratorio de Ecología del CEAMA
Instituto Interuniversitario de Investigación del Sistema Tierra en Andalucía. Universidad de Granada
Avda. del Mediterráneo s/n. 18006 Granada, España

María Teresa Bonet García
mterebonet@gmail.com
Departamento de Historia Medieval y Ciencias y Técnicas Historiográficas, Facultad de Filosofía y Letras
Universidad de Granada
Campus Universitario de Cartuja. 18011 Granada, España

Francisco José Bullejos Carrillo
fjbullejos@gmail.com
Department of Biology, Center of Ecological and Evolutionary Synthesis (CEES)
University of Oslo
P.O. BOX 1066 Blindern, 0316 Oslo, Norway

Andrés Caballero Calvo
andrescaballero@ugr.es
Instituto de Desarrollo Regional
Universidad de Granada
C/ Rector López Argüeta, s/n. 18071 Granada, España

Javier Cabello Piñar
jcabello@ual.es
Departamento de Biología y Geología
Centro Andaluz para la Evaluación y Seguimiento del Cambio Global, Universidad de Almería
Ctra. Sacramento s/n. 04120 La Cañada de San Urbano (Almería), España

Francisco Mario Cabezas Arcas
fmca.rfe@gmail.com
Laboratorio de Ecología del CEAMA
Instituto Interuniversitario del Sistema Tierra en Andalucía. Universidad de Granada
Avda. del Mediterráneo s/n. 18006 Granada, España

Francisco Javier Cano-Manuel León
franciscoj.canomanuel@juntadeandalucia.es
Área de Conservación, Espacio Natural de Sierra Nevada
Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía
Carretera Antigua de Sierra Nevada, Km 7. 18191 Pinos Genil (Granada), España

Presentación Carrillo Lechuga
pcl@ugr.es
Departamento de Ecología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Jorge Castro Gutiérrez
jorge@ugr.es
Departamento de Ecología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

José Antonio Delgado Molina
jadelmo@ugr.es
Departamento de Ecología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Francisco Domingo Poveda
poveda@eeza.csic.es
Departamento de Desertificación y Geoecología.
Estación Experimental de Zonas Áridas
Consejo Superior de Investigaciones Científicas (CSIC)
Ctra. Sacramento s/n. 04120 La Cañada de San Urbano (Almería), España

María del Carmen Fajardo Merlo
mfajardo@agenciamedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

Jesús Fornieles Callejón
jforniel@ugr.es
Departamento de Electromagnetismo y Física de la Materia, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Miguel Galiana García
mgaliana@agenciamedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

Francisco Javier Galindo Parrilla
fgalindo@agenciamedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

José María Gil Sánchez
jmgilsanchez@yahoo.es
Wilder SOUTH
Sociedad para el Estudio, Observación y Conservación de la Biodiversidad Mediterránea
Dr. Prados Picazo 10, 4ºB. 18230 Atarfe (Granada), España

Antonio Gómez Ortiz
gomez@triuium.gh.ub.es
Grupo de Investigación Paisatge y paleoambients a la muntanya mediterrània y Servei de Paisatge. Facultat de Geografia i Història
Universidad de Barcelona
C/ Montalegre 6-8, 3ª planta. 08001 Barcelona, España

Adela González Megías
adelagm@ugr.es
Departamento de Zoología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Emilio González Miras
egmiras@agenciademedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Almería
Consejería de Medio Ambiente y Ordenación del
Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

José Enrique Granados Torres
josee.granados.ext@juntadeandalucia.es
Agencia de Medio Ambiente y Agua.
Área de Conservación, Espacio Natural de Sierra Nevada
Consejería de Medio Ambiente y Ordenación del
Territorio, Junta de Andalucía. Carretera Antigua de Sierra
Nevada, Km 7. 18191 Pinos Genil (Granada), España

Javier Herrero Lantarón
herrero@ugr.es
Grupo de Dinámica Fluvial e Hidrología
Instituto Interuniversitario de Investigación del Sistema
Tierra en Andalucía. Universidad de Granada
Avda. del Mediterráneo s/n. 18006 Granada, España

José Antonio Hódar Correa
jhodar@ugr.es
Departamento de Ecología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Gonzalo Jiménez Moreno
gonzaloj@ugr.es
Departamento de Estratigrafía y Paleontología, Facultad
de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Yolanda Jiménez Olivencia
yjimenez@ugr.es
Instituto de Desarrollo Regional
Universidad de Granada
C/ Rector López Argüeta, s/n. 18071 Granada, España

Andrew Kowalski
andyk@ugr.es
Departamento de Física Aplicada, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

María Rosa López Onieva
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del
Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

Rogelio López Sanjuan
rlopezs@agenciademedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del
Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

Javier Martín Jaramillo
jmartinj@agenciademedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del
Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

Berta Martín López
berta.martin@uam.es
Laboratorio de Socio-Ecosistemas, Departamento
de Ecologia
Universidad Autónoma de Madrid
C/ Darwin 2. Edificio Biología. 28049 Madrid, España

José María Martín Civantos
civantos@ugr.es
Departamento de Historia Medieval y Ciencias y Técnicas
Historiográficas, Facultad de Filosofía y Letras
Universidad de Granada
Campus Universitario de Cartuja. 18011 Granada, España

Juan Manuel Medina Sánchez
jmmedina@ugr.es
Departamento de Ecología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Rosa Menéndez Martínez
r.menendez@lancaster.ac.uk
Department of Biological Sciences, Lancaster
Environment Centre
Lancaster University
LA1 4YQ. Lancaster, United Kingdom

Joaquin Molero Mesa
jmolero@ugr.es
Departamento de Botánica, Facultad de Farmacia
Universidad de Granada
Campus Universitario de Cartuja. 18011 Granada, España

Carlos Montes del Olmo
carlos.montes@uam.es
Laboratorio de Socio-Ecosistemas, Departamento de
Ecologia
Universidad Autónoma de Madrid
C/ Darwin 2, Edificio Biología. 28049 Madrid, España

Rafael Morales Baquero
rmorales@ugr.es
Departamento de Ecología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España
-
Instituto del Agua
Universidad de Granada
C/ Ramón y Cajal, 4. 18071 Granada, España

Ricardo Antonio Moreno Llorca
ricuni@ugr.es
Laboratorio de Ecología del CEAMA
Instituto Interuniversitario de Investigación del Sistema
Tierra en Andalucía. Universidad de Granada
Avda. del Mediterráneo s/n. 18006 Granada, España

José Miguel Muñoz Díaz
jmmunoz@agenciamedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del
Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

Francisco Javier Navarro Gómez-Menor
franciscoj.navarro@juntadeandalucia.es
Área de Conservación, Espacio Natural de Sierra Nevada
Consejería de Medio Ambiente y Ordenación del
Territorio, Junta de Andalucía
Carretera Antigua de Sierra Nevada, Km 7. 18191
Pinos Genil (Granada), España

Irene Navarro González
irenavarrog@gmail.com
Laboratorio de Ecología del CEAMA
Instituto Interuniversitario de Investigación del Sistema
Tierra en Andalucía. Universidad de Granada
Avda. del Mediterráneo s/n. 18006 Granada, España

Marc Oliva Franganillo
oliva_marc@yahoo.com
Instituto de Geografia e Ordenamento do Território,
Centro de Estudos Geográficos
Universidade de Lisboa
Edifício da Faculdade de Letras, Alameda da
Universidade, 1600-214 Lisboa, Portugal

Cecilio Oyonarte Gutiérrez
coyonart@ual.es
Departamento de Agronomía
Universidad de Almería
Edificio Científico Técnico II-B, Ctra. Sacramento s/n.
04120 La Cañada de San Urbano (Almería), España

Ignacio Palomo
ignacio.palomo@uam.es
Basque Centre for Climate Change (BC3)
Alameda de Urquijo 4. 48008 Bilbao, España
-
Laboratorio de Socio-Ecosistemas, Departamento de
Ecologia
Universidad Autónoma de Madrid
C/ Darwin 2, Edificio Biología. 28049 Madrid, España

José Vicente Pérez Peña
vperez@ugr.es
Departamento de Geodinámica, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Enrique Pérez Sánchez-Cañete
enripsc@ugr.es
Departamento de Física Aplicada, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Antonio Jesús Pérez-Luque
ajperez@ugr.es
Laboratorio de Ecología del CEAMA
Instituto Interuniversitario de Investigación del Sistema
Tierra en Andalucía. Universidad de Granada
Avda. del Mediterráneo s/n. 18006 Granada, España

Ramón Pérez Pérez
ramon@ugr.es
Laboratorio de Ecología del CEAMA
Instituto Interuniversitario de Investigación del Sistema
Tierra en Andalucía. Universidad de Granada
Avda. del Mediterráneo s/n. 18006 Granada, España

Carmen Pérez Martínez
cperezm@ugr.es
Departamento de Ecología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Laura Porcel Rodríguez
lporcel@ugr.es
Instituto de Desarrollo Regional
Universidad de Granada
C/ Rector López Argüeta, s/n. 18071 Granada, España

Jorge Portí Durán
jporti@ugr.es
Departamento de Física Aplicada, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Andrés Reyes Díez
areyesdiez@gmail.com
Departamento de Biología y Geología
Centro Andaluz para la Evaluación y Seguimiento del Cambio Global
Universidad de Almería
Ctra. Sacramento s/n. 04120 La Cañada de San Urbano (Almería), España

Silvia Rubio Rubio
srubio@agenciamedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

Marta Sáinz Bariáin
msainzb@ugr.es
Departamento de Zoología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Alfonso Salinas Extremera
asalinas@ugr.es
Departamento de Electromagnetismo y Física de la Materia, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Montserrat Salvà Catarineu
salva@ub.edu
Grupo de Investigación Paisatge y paleoambients a la muntanya mediterrània y Servei de Paisatge. Facultat de Geografia i Història
Universidad de Barcelona
c/ Montalegre 6-8, 3ª planta. 08001 Barcelona, España

Ferrán Salvador Franch
fsalvador@ub.edu
Grupo de Investigación Paisatge y paleoambients a la muntanya mediterrània y Servei de Paisatge. Facultat de Geografia i Història
Universidad de Barcelona
c/ Montalegre 6-8, 3ª planta. 08001 Barcelona, España

Cristina Patricia Sánchez Rojas
cpsanchez@agenciamedioambienteyagua.es
Agencia de Medio Ambiente y Agua de Andalucía.
Gerencia Provincial de Granada
Consejería de Medio Ambiente y Ordenación del Territorio, Junta de Andalucía
C/ Joaquina Eguaras, 10. 18013 Granada, España

Penélope Serrano Ortiz
penelope@ugr.es
Departamento de Ecología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Alberto Tinaut Ranera
hormiga@ugr.es
Departamento de Zoología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Manuel Villar Argaiz
mvillar@ugr.es
Departamento de Ecología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Carmen Zamora Muñoz
czamora@ugr.es
Departamento de Zoología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España

Regino Jesús Zamora Rodríguez
rzamora@ugr.es
Departamento de Ecología, Facultad de Ciencias
Universidad de Granada
Avda. Fuentenueva s/n. 18071 Granada, España
-
Laboratorio de Ecología del CEAMA
Instituto Interuniversitario de Investigación del Sistema Tierra en Andalucía. Universidad de Granada
Avda. del Mediterráneo s/n. 18006 Granada, España

View of the Trevenque Peak

Observatorio
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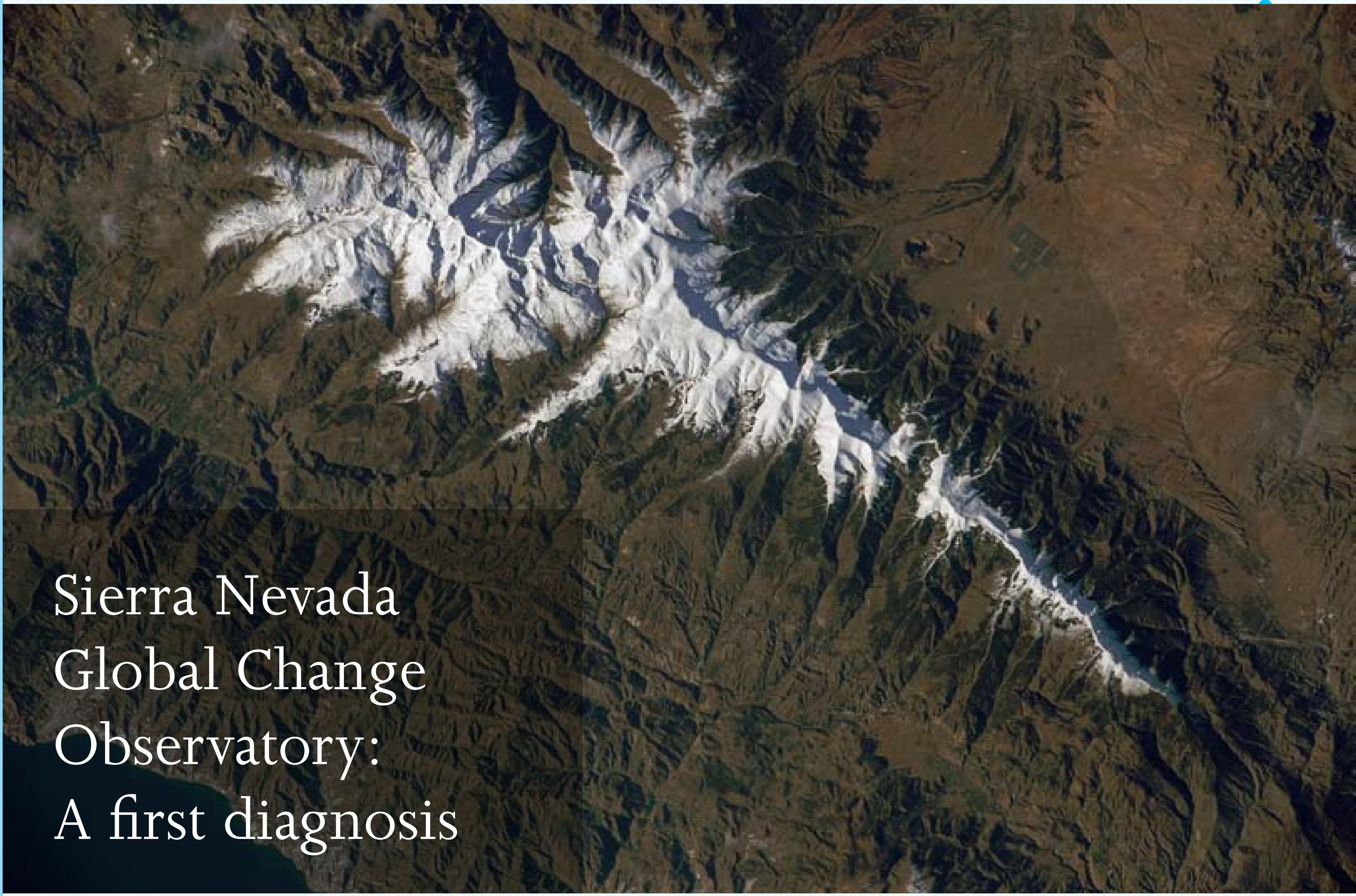
Introduction

View of Sierra Nevada from the International Space Station, taken in December 2014 (image courtesy of *"Earth Science and Remote Sensing Unit, NASA Johnson Space Center"*)



Sierra Nevada Global Change Observatory: A first diagnosis

The environmental and socioeconomic problems generated by global change constitute the most important challenge that our society is facing. Nowadays, there is a general consensus on the magnitude of the changes in the planet due to the impact caused by human activities. The atmosphere and the ocean is warming up and the CO_2 concentrations have risen to unprecedented levels [1]. We are currently in an era of change, a new stage in the history of the Earth, dominated by humans: the Anthropocene [2].

For the Mediterranean basin, most climatic models predict higher temperatures, less precipitation, and increase of climatic variability [3]. The socioeconomic consequences of global changes become more acute in Mediterranean ecosystems for their long history of human exploitation, which can provoke more complex ecological responses [4].

Despite the uncertainty concerning the climatic predictions, there are enough scientific information to manage the transition of our ecosystems within a context of global change. This knowledge is of great value for environmental managers to take decisions based on relevant and up-to-date information.

We live now in a new era, the Anthropocene, and we need observatories to survey the health of the planet. In a global change scenario, a protected area such as Sierra Nevada, should serve as a natural laboratory enabling long-term evaluations of ecosystem responses as well as testing their adaptive capacity [10]. Due to its geographical position in southern Europe and the breadth of its elevational range, Sierra Nevada is an unique watchtower to observe global processes.

The history of ecosystem management of Sierra Nevada in the past is quite different from the current one, and the future promises climatic scenarios and perturbation regimes far different from the past or present ones. This dynamic reality requires new focus on the management of the natural environment, which includes as basic aims the fostering of ecological integrity and resilience [6].

Sierra Nevada Global-Change Observatory

Sierra Nevada forms part of the first World Green List of Well-Managed Protected Areas, which has been accredited by the International Union of Conservation of Nature (IUCN) in 2014. One important part of this recognition is related to a management model based on the transfer of scientific knowledge, social participation, and institutional coordination. In this model, the Sierra Nevada Global Change Observatory plays a fundamental role [5].

Since 2007, Sierra Nevada Global Change Observatory has undergone an ambitious project promoted by the Environmental and Regional Planning Council of the Regional Government of Andalusia, with the scientific coordination of the University of Granada—Andalusian Environmental Centre (IISTA, Inter-University Institute of Research of Earth Systems in Andalusia) and with the collaboration of the Spanish National Park Service, in order to develop a monitoring and information-management programme [9].

The design of the monitoring programme was based on the conceptual framework and the thematic categories proposed by the GLOCHAMORE initiative (GLObal CHAnge in MOuntain REgions http://mri.scnatweb.ch/en/projects/glochamore), under the auspices of UNESCO.

Our monitoring programme 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 [8]. Monitoring methodologies were defined to evaluate both the state of the key ecological functions, such as the structure of the main ecosystems in Sierra Nevada, and the possible impact of global change on Sierra Nevada [7].

The programme promotes the collaboration between the different teams belonging to various institutions (researchers from the University of Granada and other academic institutions at the national and international levels, as well as decision makers) in order to plan transversal work with integrative objectives. The chapters of this book, signed by 69 authors belonging to different organizations and public institutions, constitute a notable sampling of the synergy generated. This commitment is reflected by the involvement of the Sierra Nevada Global Change Observatory in the design and implementation of other similar initiatives with regional (Andalucian Network of Global Change Observatories), national (Spanish Network of Global Change Observatories) and international scope (LTER, LifeWatch, specific Horizon 2020 and LIFE projects).

LONG-TERM MONITORING

STANDARDIZED PROTOCOLS TO QUANTIFY BIOPHYSICAL AND SOCIO-ECONOMICAL KEY VARIABLES

INTEGRAL MANAGEMENT OF THE INFORMATION GENERATED

KNOWLEDGE FOR ADAPTATION

Our programme pursues the following general goals:

- To assess, using standardized methodological protocols, the functioning of the ecosystems of the Sierra Nevada Protected Area, its natural processes, and its dynamics, in a long-term perspective.
- To know the population dynamics, phenological variations, and conservation problems of different key organisms as indicators of ecological processes that can be affected by global change.
- To identify the possible effects of global change on the species, ecosystems, and natural resources, providing a vision of the trends of change.
- To design mechanisms to evaluate the effectiveness of the management activities undertaken in Sierra Nevada.

In short, our programme is intended to diagnose the degree of ecosystem sensitivity to changes, and their adaptation capacity, fostering resistance and resilience of the ecosystems through suitable management actions.

Scientific knowledge for adaptive management

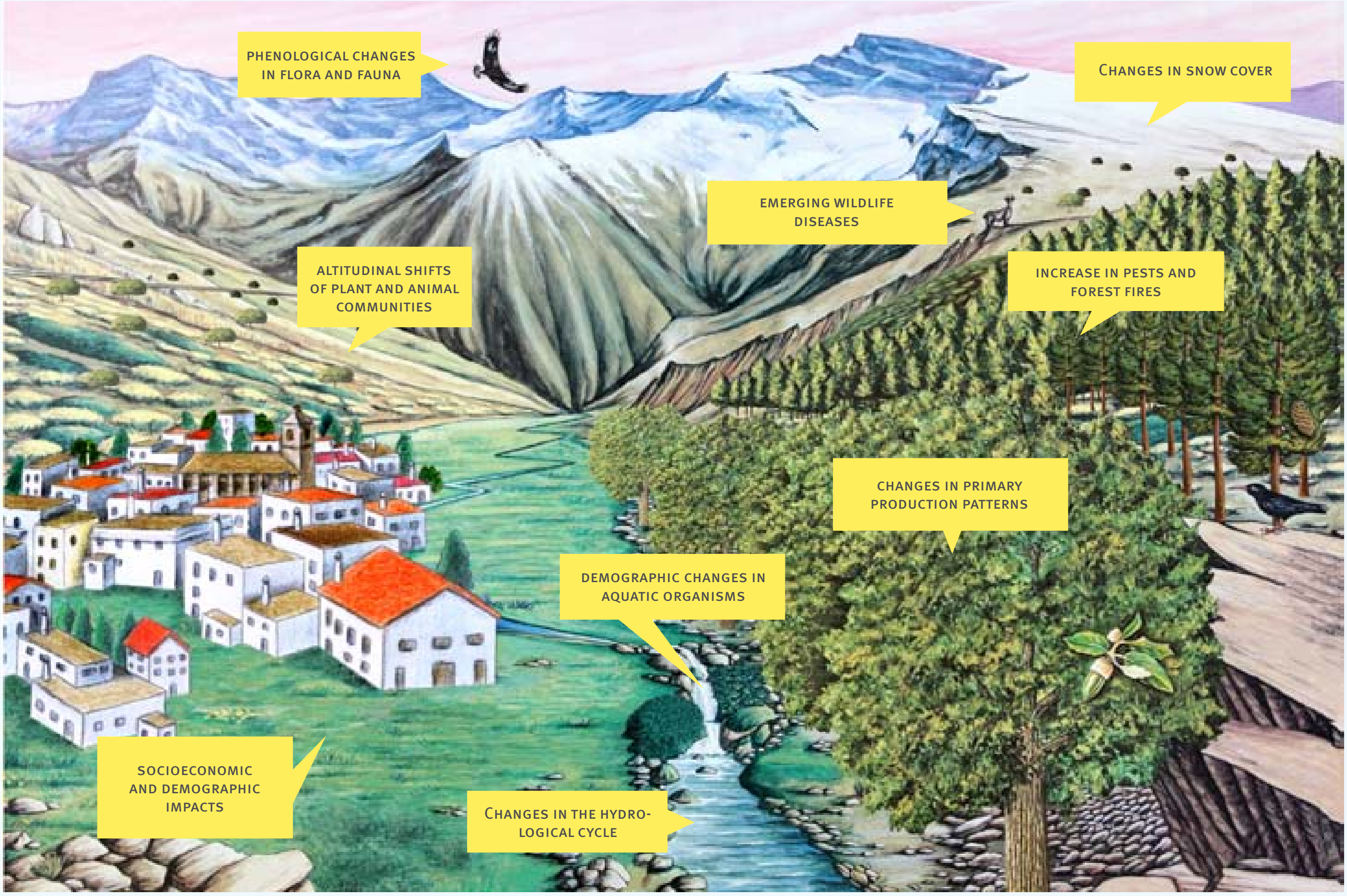
A major premise of our project is that environmental management should be supported by the most up-to-date tested scientific-technical knowledge. We have put into practice this philosophy, proposing key questions from the outset, defining the goals to be pursued with the actions undertaken, and specifying the methodological and analytical details necessary to address them. To this, we add the spatial and temporal dimensions of the actions and their monitoring, planning the work that should be carried out, and the different stakeholders involved.

All of the projects that we have undertaken with this new philosophy lie within a conceptual framework of reference and planning based on hypotheses (formulated as questions) concerning the functioning of ecological systems and their expected responses.

What have we learned about global change effects on the ecosystems of Sierra Nevada?

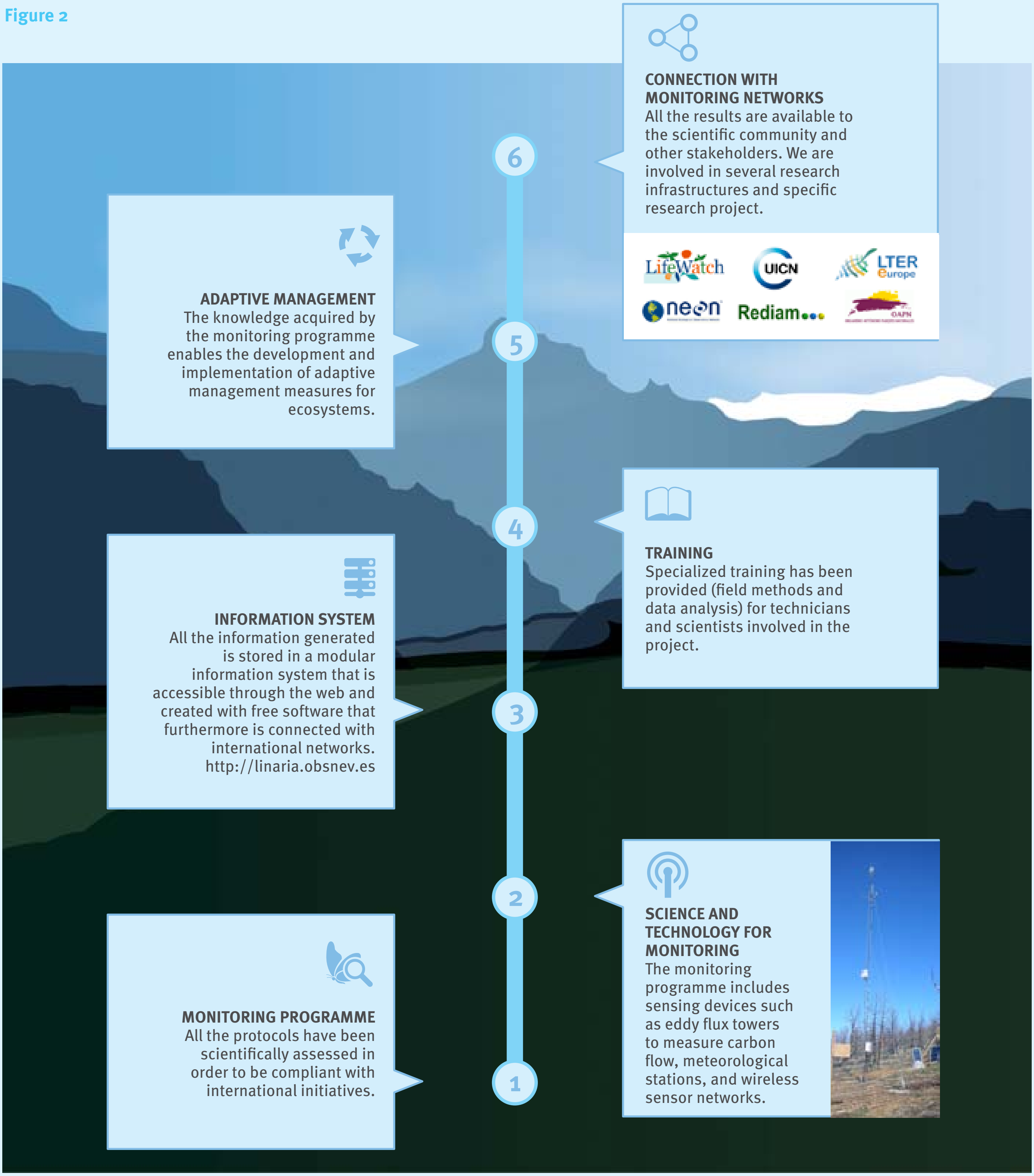
We now have valuable information compiled over the last few decades, which comes from the work of researchers, managers, and technical personnel in charge of conservation. Thanks to this common effort, a number of hypotheses concerning the impact of global change have been formulated for Sierra Nevada (Figure 1). To prepare this document, we have collected information both from the monitoring programme of the Sierra Nevada Global Change Observatory as well as the research groups that have been working for decades in this context (see Figure 6).

Figure 1



Hypothesis of the impact of global change in Sierra Nevada

Figure 2

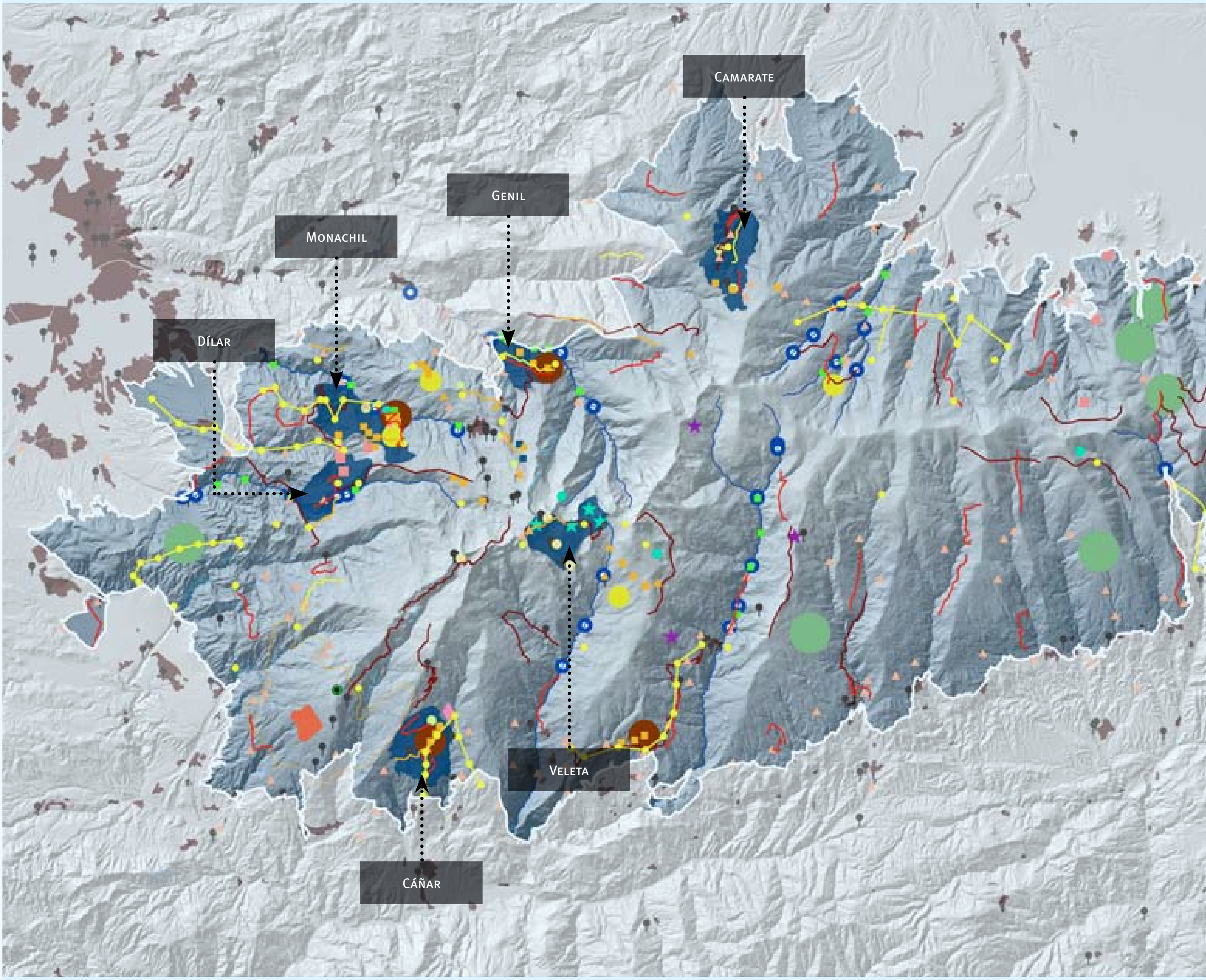


Main achievements of the Sierra Nevada Global Change Observatory

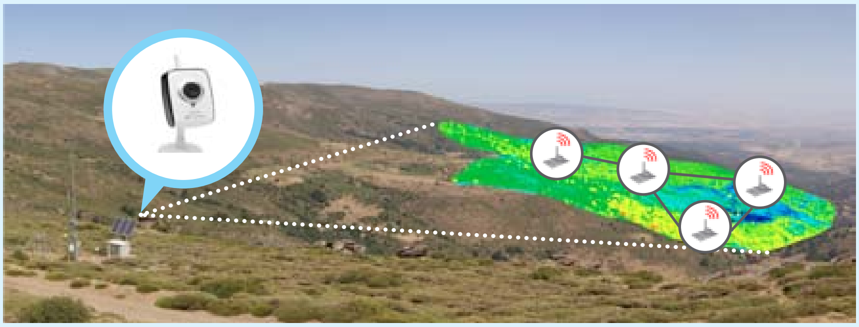
To study the potential effects of global change in a territory, it is not sufficient to measure biophysical variables using standardized protocols. It is also necessary for the sampling points to be spatially distributed according to specific objectives in order to optimise and streamline the gathering of environmental information. For this reason, we have developed the concept of the Intensive Monitoring Station (hereinafter IMS): areas with a high density of ecological protocols around a meteorological station. This conceptual framework has proved especially useful for orienting the data collection towards certain types of ecosystems and to permit the integration of our programme into other international initiatives.

Each IMS is located in a major ecosystem of the Sierra Nevada (high summits, Quercus forests, high-mountain shrublands, semiarid thickets, or pine plantations). Also, in each IMS, there is at least one meteorological station with different sensors. Near these stations, the biological and ecological variables of the programme are monitored. In addition, information has been collected on the snow cover and the photosynthetic activity of each IMS based on satellite images. Finally, the installation of wireless sensor networks have been planned in several IMS. All the data generated is stored in an information system.

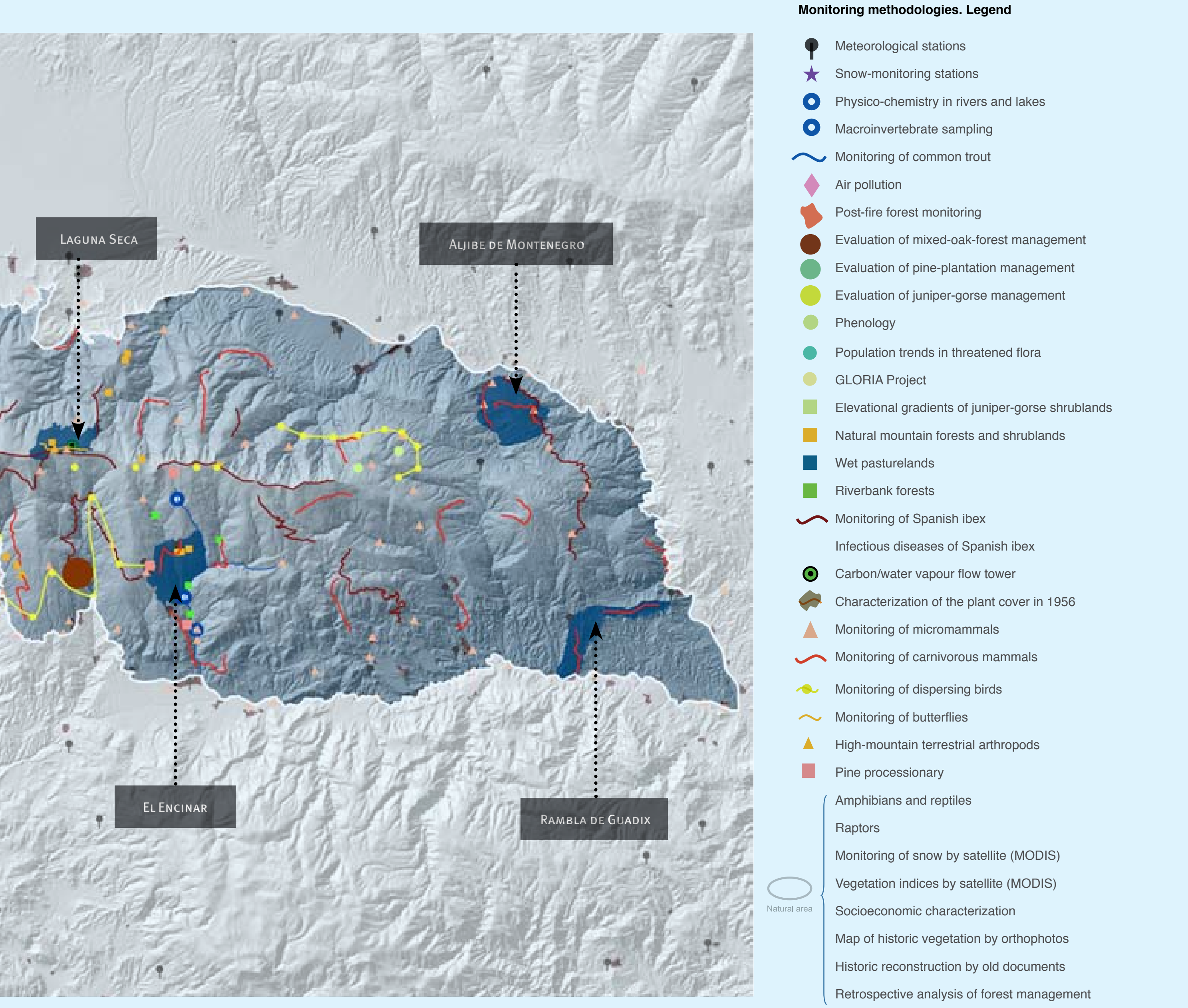
Figure 3



Spatial distribution of the sampling points of the monitoring programme and Intensive Monitoring Stations



In the Intensive Monitoring Station at Cáñar, a wireless sensor network was installed together with a camera to quantify the photosynthetic activity using vegetation indices.

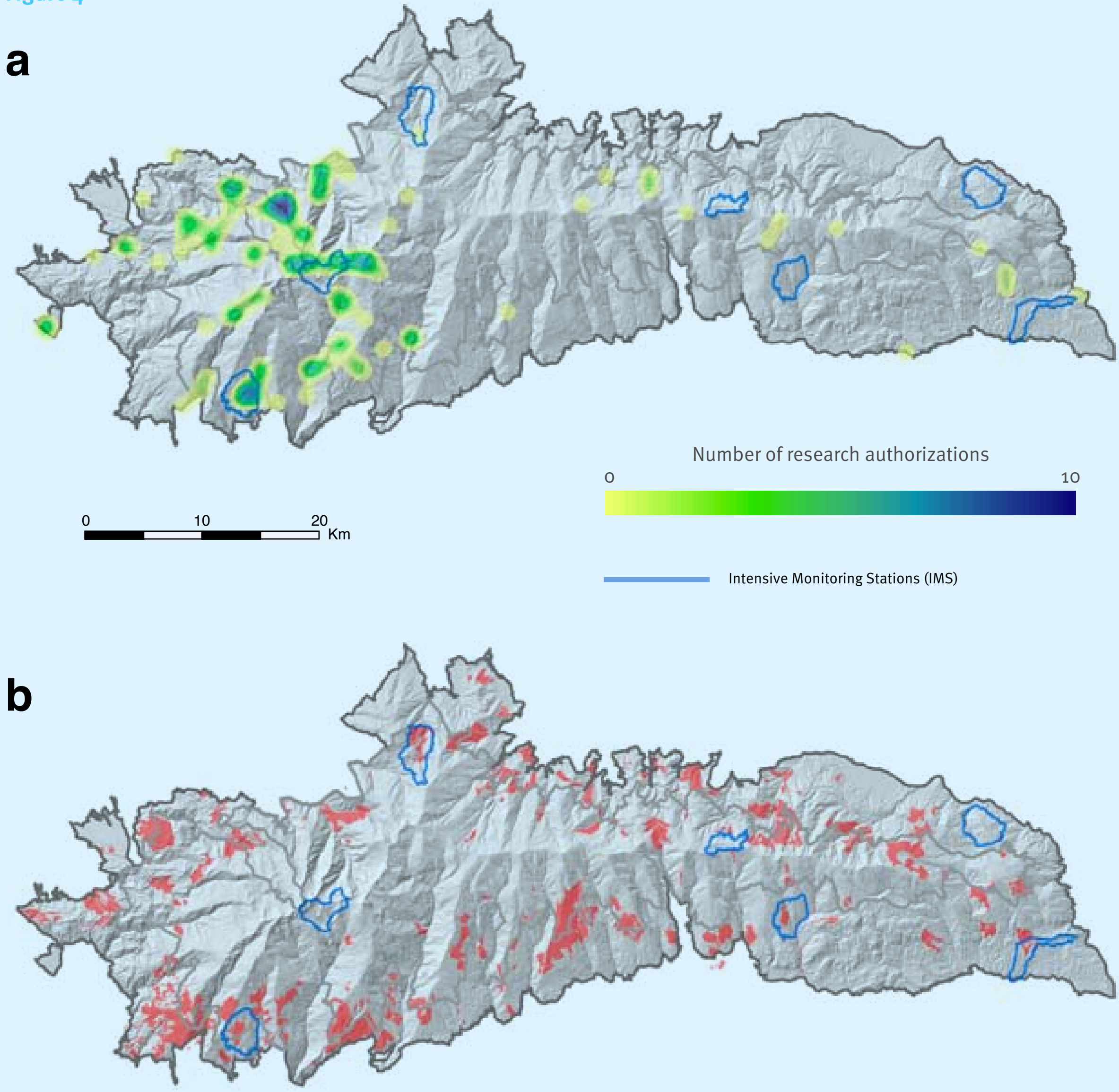


Spatial location of the research projects and forest-management actions undertaken in Sierra Nevada

The map in the Figure 4a shows where the research projects have been performed in Sierra Nevada during the years 2009-2013.

Figure 4b shows the spatial distribution of the main forest-management actions (pine plantations, forest treatments, etc.) conducted in Sierra Nevada from 1992 to 2014. In both maps, the distribution of the IMS is superimposed.

Figure 4



(a) Location of research projects in Sierra Nevada during 2009-2013. (b) Spatial distribution of forest-management activities from 1992 to 2014 in Sierra Nevada

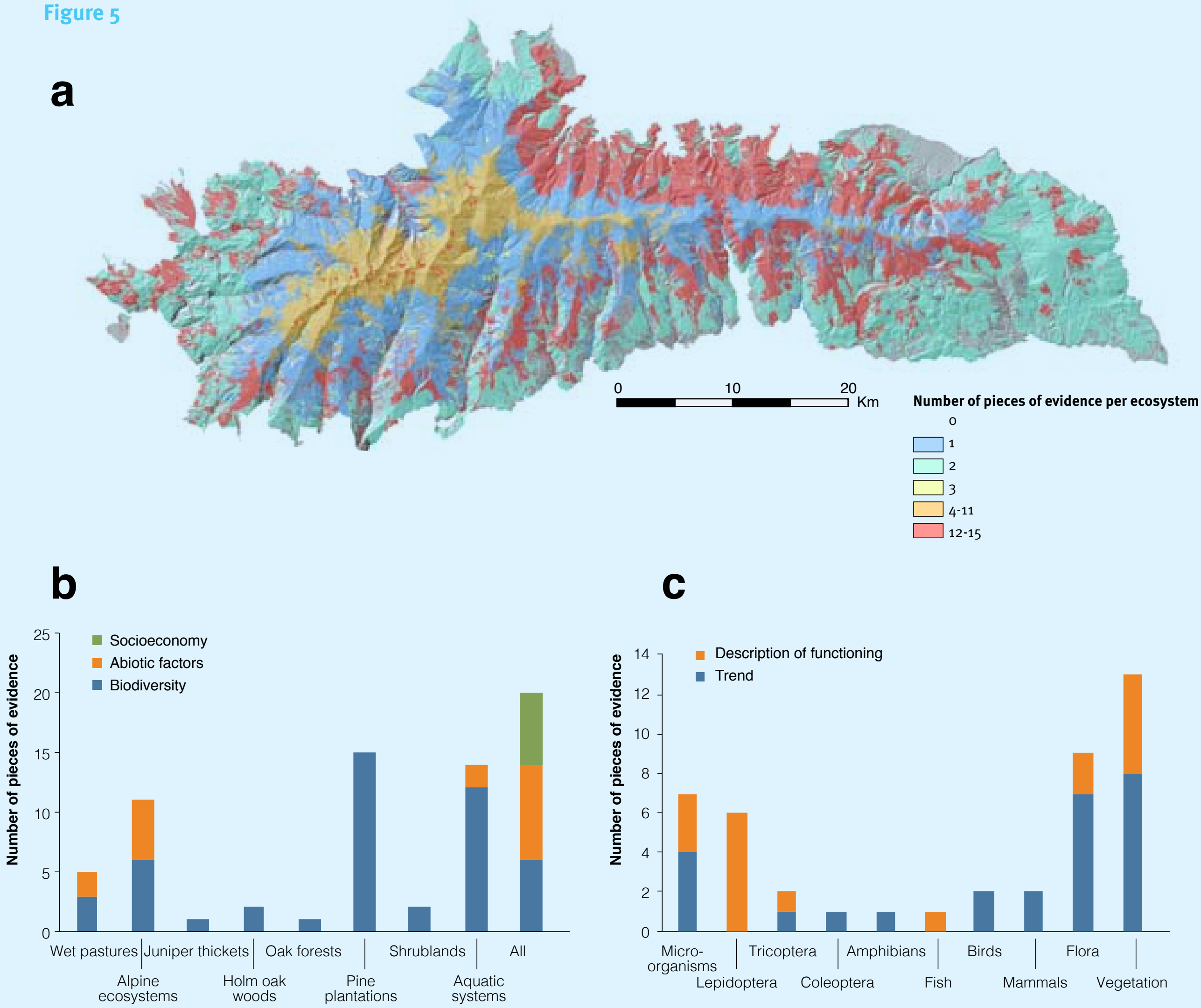
Summary of the results found by Sierra Nevada Global Change Observatory

This book provides detailed descriptions of the impact of global change on Sierra Nevada ecosystems. In total, we have compiled 84 evidences that can be classified according to different criteria.

High-mountain ecosystems, aquatic systems (rivers and lakes) and pine plantations are the ecosystems with higher number of evidences.

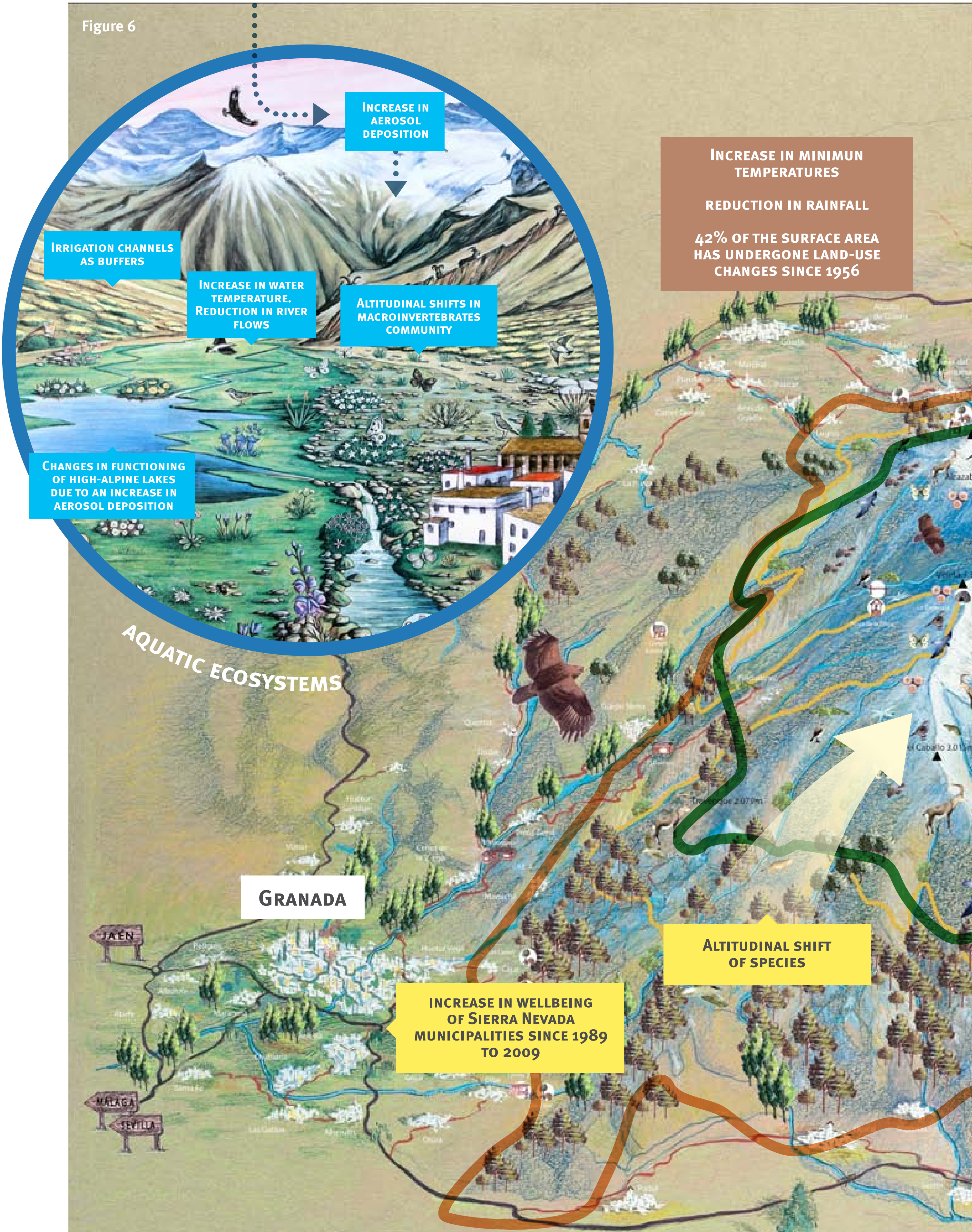
Also, the evidences can be classified according to the taxa affected and their role as indicators of the process (Figure 5c), or in terms of how they affect abiotic or biotic factors (Figure 5b). Some examples provide information on trends while others describe the functioning of the processes (e.g. cause-effect relations).

Figure 5

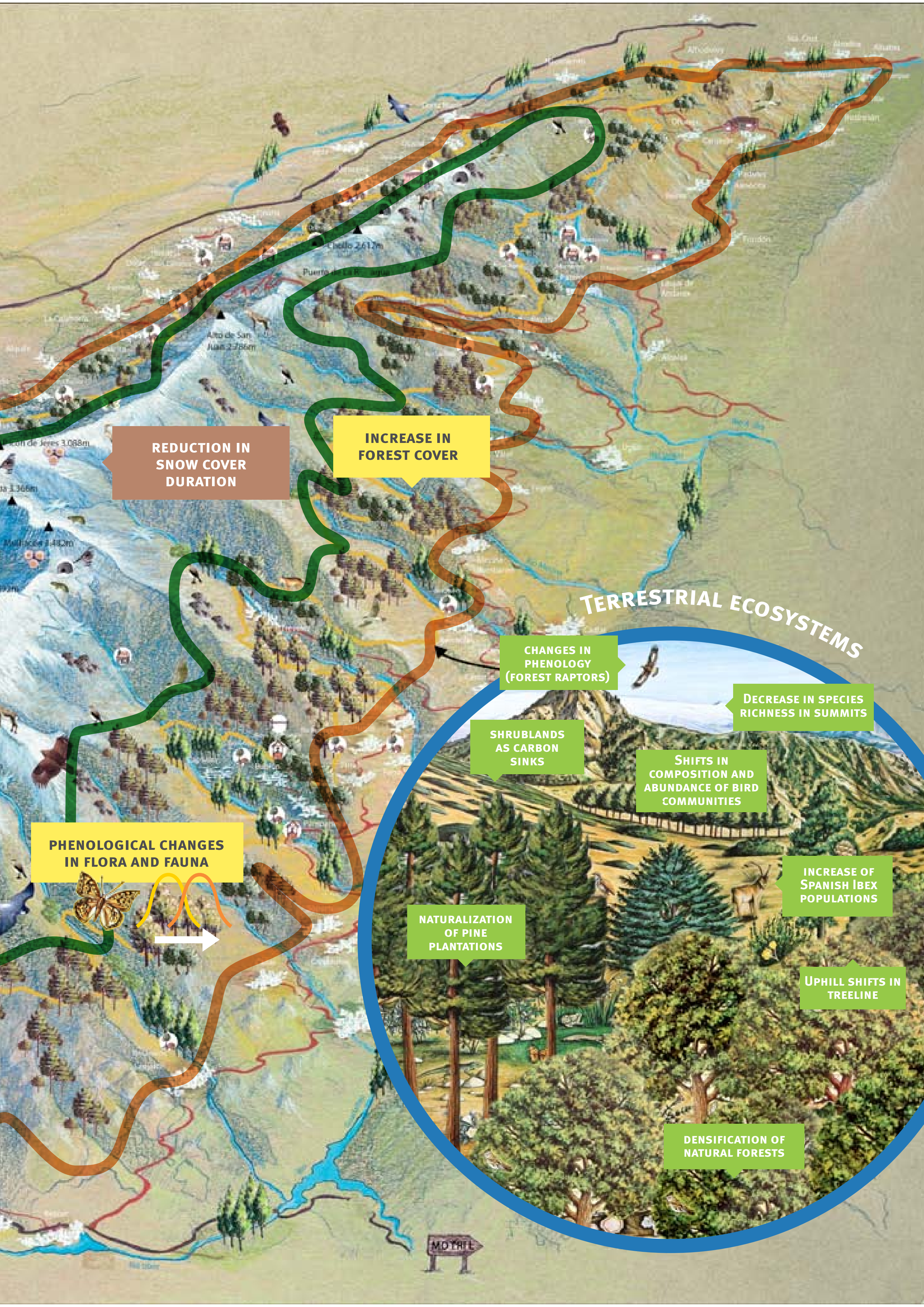


(a) Spatial distribution of the pieces of evidence of global change by ecosystem. (b) Classification of evidence by type and ecosystem. (c) Type of evidence per taxon affected.

Figure 6



Summary of the results found by the Sierra Nevada Global Change Observatory



REDUCTION IN SNOW COVER DURATION
INCREASE IN FOREST COVER
PHENOLOGICAL CHANGES IN FLORA AND FAUNA
TERRESTRIAL ECOSYSTEMS
CHANGES IN PHENOLOGY (FOREST RAPTORS)
DECREASE IN SPECIES RICHNESS IN SUMMITS
SHRUBLANDS AS CARBON SINKS
SHIFTS IN COMPOSITION AND ABUNDANCE OF BIRD COMMUNITIES
INCREASE OF SPANISH IBEX POPULATIONS
NATURALIZATION OF PINE PLANTATIONS
UPHILL SHIFTS IN TREELINE
DENSIFICATION OF NATURAL FORESTS
MOTRIL

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› More references at http://refbase.iecolab.es/ref_dossier_resultados.html

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Chapter 1

Clouds (*Undulatus asperatus*) over Sierra Nevada

Past climate trends and projections for the future

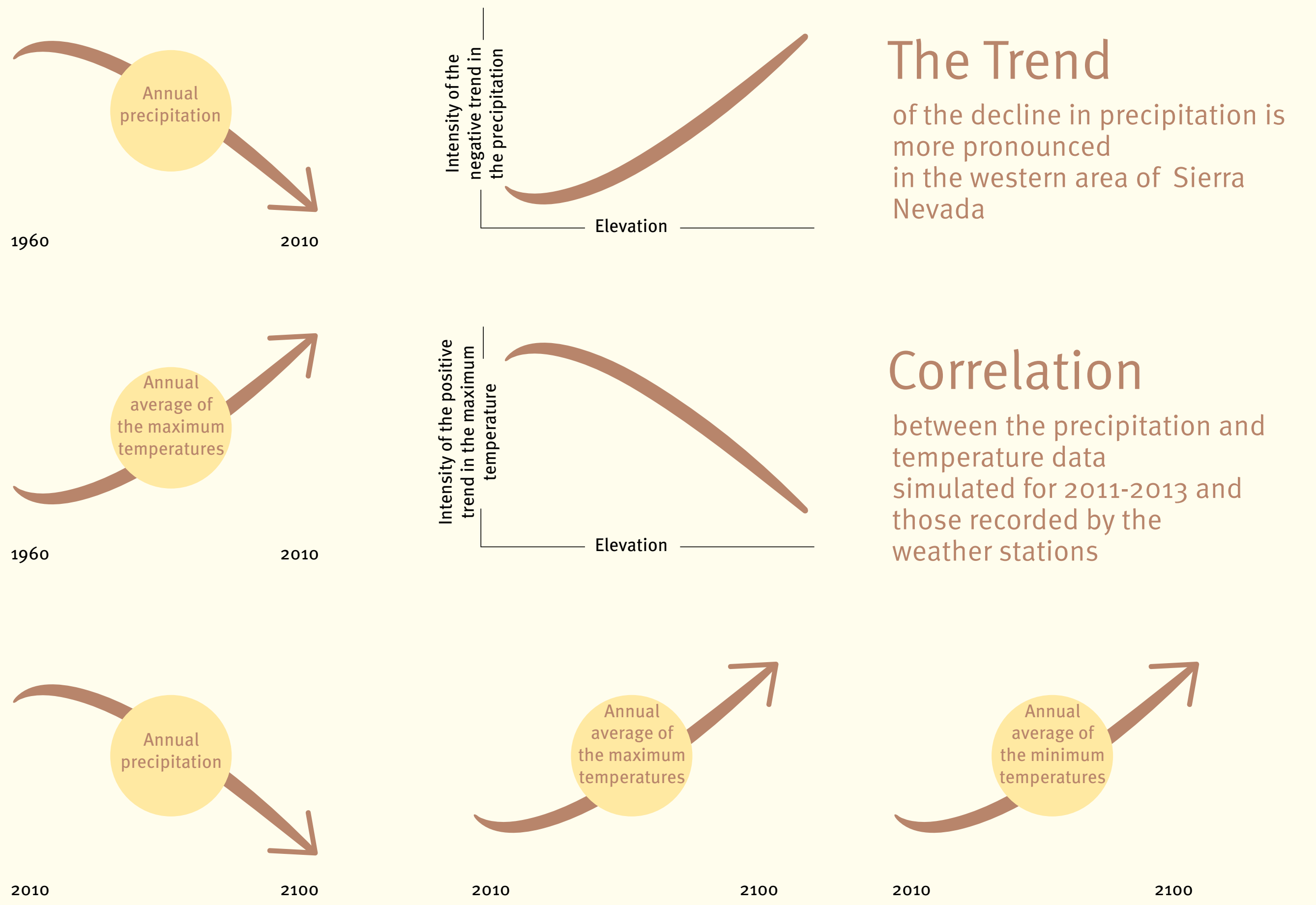
Climatic variables are key to explain the functioning, distribution, and structure of the earth's ecosystems. Climate change provoked by human activities (e.g. greenhouse-gas emissions) will have far-reaching ecological and socio-economic consequences (according to the Intergovernmental Panel on Climate Change, the IPCC). The study and analysis of climate is essential to understand both the functioning of ecosystems as well as the mechanisms of service provision and possible changes triggered by human activity.

These ideas have been incorporated into the monitoring programme of the Sierra Nevada Global Change Observatory since its inception in 2007, with a major investment in the setting up of weather stations to characterize mountain climate. Also, data have been compiled from a dozen stations.

This information has made it possible to generate annual maps of climatic variables of great interest (maximum-minimum temperature, precipitation for a time series from 1960 to 2010).

In addition, with respect to the future climatic scenarios forecast by the IPCC, maps have been drawn of the same climatic variables in Sierra Nevada for all the years of the 21st century. These maps have enabled certain preliminary analyses that characterize both the climate of the Sierra Nevada as well as some of the possible trends of change during the last few decades.

This chapter presents the results found in this context, which are closely related to those described in Chapter 2. In turn, the trends and patterns noted in the snow and the general climate are the causal factors for many of the biotic responses analysed in other chapters of this book (Chapters 4, 5, 6, and 7).



Summary of the main results described in this chapter. The temporal trends for the climatic variables are shown from 1960 to the present. The future projections are also shown. The variation of the trend over the elevation is shown for the precipitation and maximum temperature variables.

The analysis of the climate maps made by interpolation between 1960 and 2010 provided results consistent with other findings for the Mediterranean basin in the same time period. A trend towards reduced precipitation was found throughout almost the entire Sierra Nevada. This trend is stronger as altitude increases. In addition, the trend towards lower precipitation is more acute in the western area of Sierra Nevada.

With respect to maximum temperature there is a trend towards an increase throughout most of Sierra Nevada. As with precipitation, this trend is more intense at high elevations. An analysis of the time series of the simulated data of the above variables for the 21^{st} century indicates a sharp rise in the annual average of maximum temperatures and another less intense rise in the annual average of minimum temperatures. Finally, there was a fall in precipitation. A comparison of the climate data (maximum/minimum temperatures and precipitation) taken at 7 weather stations in Sierra Nevada with simulated values for the years 2011-2013 shows a high correlation. This signifies that, at least in the years analysed, the predictions for the future climatic scenario were largely being fulfilled.

1.1. Climate change over the last 50 years in Sierra Nevada

Pérez-Luque, A.J.; Pérez-Pérez, R.; and Bonet, F.J

Andalusian Institute for Earth System Research. University of Granada

Abstract

The analysis of the climate data available for the Sierra Nevada Global Change Observatory has revealed an increase in temperatures over the last 50 years, this being more evident in the maximum temperatures than in the minimum ones, over the period analyzed. The temporal evolution of precipitation showed a general decline, showing a differential pattern between the eastern and western areas of Sierra Nevada. The trends were more pronounced in the western areas of Sierra Nevada.

Aims and methodology

High-resolution (100 m) climate maps have been created for Sierra Nevada using the variables of annual precipitation, annual average of minimum temperatures, and annual average of maximum temperatures [1]. These maps, representing the climate observed in Sierra Nevada for the period 1960-2010, are available from the Sierra Nevada Global Change Observatory.

The temporal trend of each variable in the study period in Sierra Nevada was analysed. For this, trend-analysis techniques were applied (Mann-Kendall test) in such a way that for each climatic variable, the trends were characterized at the pixel level quantifying their magnitude, identifying their sign (positive or negative) and determining whether the trend was significant for the period analysed (50 years). Next, the spatial pattern of the trends of each of the variables was explored and the trends were analysed as a function of elevation.

Results

Precipitation

The results of the trend-analysis of precipitation over the last 50 years show that Sierra Nevada has undergone a decline in precipitation (99.8 % of the pixels presented negative trends). Almost half of the territory has registered a significant reduction in precipitation (43.45 % pixels with a significantly negative trend; Table 1, Figure 1). The exploration of the trends in precipitation as a function of elevation showed a clear pattern with more negative trends the higher the elevation.

Temperature

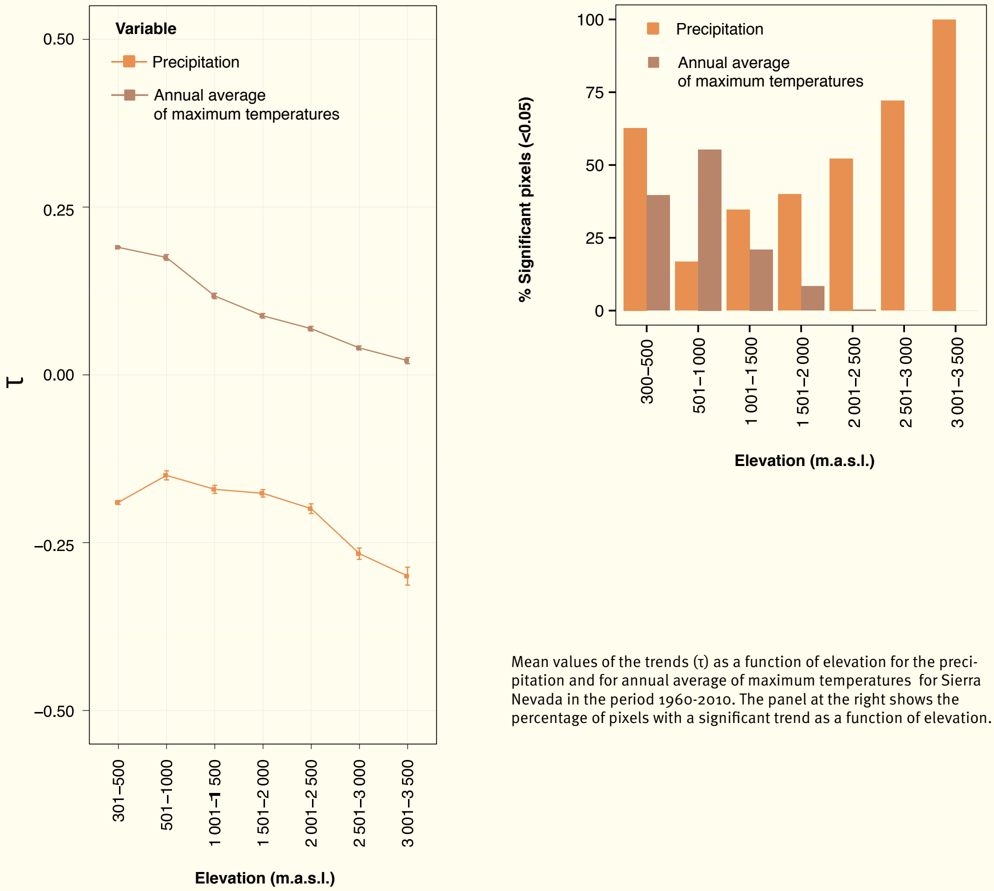
With regard to the annual average of maximum temperatures, 82.51% of the territory showed a positive trend in the last 50 years, of which 16.5% were significant trends. The spatial pattern of these trends indicates that at higher elevations, the positive trends are weaker than at lower elevations (Figure 1). For theannual average of minimum temperatures, the results of the analysis indicate that 75.5% of the territory presents positive trends, fewer than 0.01% of these being significant (Table 1).

Table 1

		Pixels		Significant pixels	
Variable	**Trend**	***n***	**%**	***n***	**%**
Precipitación	Positive Negative	298 171,460	0.17 99.79	0 74,516	0 43.37
Temperatura máxima	Positive Negative	141,757 29,551	82.50 17.19	23,417 0	13.63 0
Temperatura mínima	Positive Negative	129,759 41,762	75.52 24.30	7 0	<0.01 0

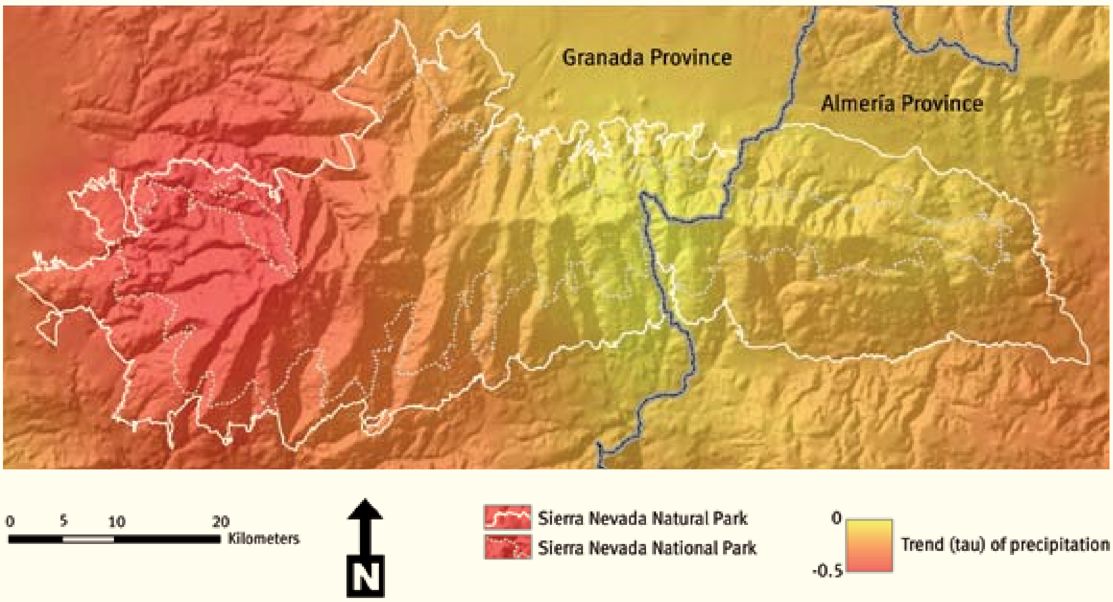
Results for the trend analysis (Mann-Kendall test) for the last 50 years regarding precipitation, annual average of maximum and annual average of the minimum temperatures. For each variable, the number of pixels is shown (n) with negative trends ($\tau < 0$) and positive trends ($\tau > 0$) as well as the number of significant pixels (p-value < 0.05).

Figure 1



Mean values of the trends (τ) as a function of elevation for the precipitation and for annual average of maximum temperatures for Sierra Nevada in the period 1960-2010. The panel at the right shows the percentage of pixels with a significant trend as a function of elevation.

Figure 2



Spatial distribution of the precipitation trends for the last 50 years. Trends (τ) with the most negative values (red) indicate a more pronounced decline in precipitation.

› Discussion and conclusions

Precipitation

The negative trends reflected in the climate maps for the last 50 years in Sierra Nevada indicate that precipitation has declined (Figure 3), in agreement with the significant decrease reported in other studies both at the regional as well as the local level [2]. This downward trend may be related to the positive trend of the NAO (North Atlantic Oscillation) index, as pointed out by other authors [3].

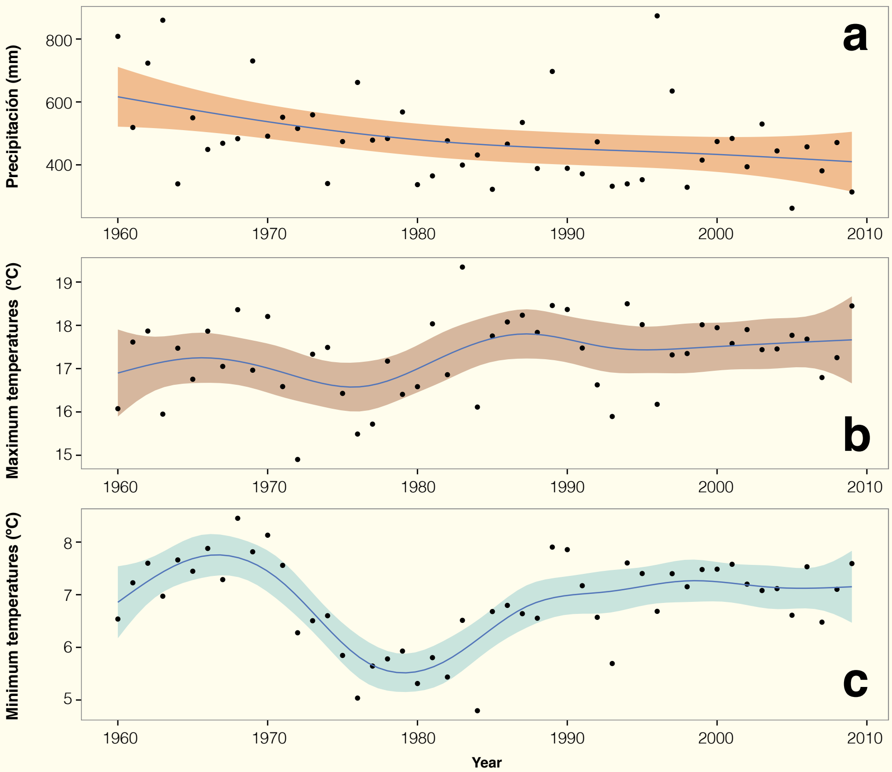
The spatial pattern of these trends reveals that the most westerly areas of Sierra Nevada have undergone the strongest trend of diminished precipitation in the last 50 years. This pattern could be due to the fact that most of the precipitation in the western and the eastern parts differs in origin. The precipitation in the western area is carried by large fronts that come from the Atlantic where the frequency and water load of these fronts is subjected to the periodic NAO pattern. By contrast, the precipitation in the eastern area comes from climatic disturbances originating in the Mediterranean Sea, and these appear to be growing as a consequence of sea warming.

In the interpretation of the general trend of precipitation, the high variability of this parameter should be taken into consideration [10] as well as the intrinsic uncertainty when generating spatial interpolations [9]. Although some studies indicate the general declining trend for the south of the Iberian Peninsula [4], this variable presents high temporal variability, obscuring the general trend [2].

Temperatures

The positive trend noted in the Sierra Nevada temperatures over the last 50 years (Figure 3) agrees with the general pattern noted in different studies at the level of both the region as well as the entire Iberian Peninsula [5, 10], indicating a significant increase in temperatures over the 20th century, particularly after the 1970s. For Sierra Nevada, significant trends have been reported for maximum temperatures, as occurs in other mountainous regions of the southern Iberian Peninsula [2, 5]. For the minimum temperatures, no significant trends were found for the entire analysed period. In this sense, various studies have demonstrated that the minimum temperatures have risen since the 1970s, this increase not being appreciable when the series from the middle of the last century is analysed [8, 10].

Figure 3



Time course of precipitation (a), annual average of maximum (b) and minimum temperatures (c), during the period 1960-2010 in Sierra Nevada. The data come from simulations for the entire Sierra Nevada. The mean values and the confidence intervals for each year are shown.

1.2. Climate in Sierra Nevada: present and future

Pérez-Luque, A.J.[1]; Pérez-Pérez, R.[1]; Aspizua, R.[2]; Muñoz, J.M.[2] and Bonet, F.J.[1]

[1] Andalusian Institute for Earth System Research. University of Granada [2] Environment and Water Agency of Andalusia

Abstract

Climate simulations forecast higher annual maximum and minimum temperatures for the end of the century in Sierra Nevada, which will vary by 2 to 6ºC for the maximum temperatures and by 1 to 4ºC for minimums. These values agree with those proposed in different studies both at the regional scale as well as for the entire Iberian Peninsula. For precipitation, the models predict a reduction although the high uncertainty of the simulations for this variable should be taken into consideration.

The values for the models show a high correlation with the real values registered by the multiparametric stations of the Sierra Nevada Global Change Observatory distributed along the steep ecological and altitudinal gradient of Sierra Nevada.

Aims and methodology

Considering the global climate models (CGCM2 and ECHAM4) and two scenarios of greenhouse-gas emissions (Table 1), regional maps for Sierra Nevada were prepared at a fine spatial resolution (100 m) for the period 2011-2100 using the variables annual precipitation, mean annual maximum temperature, and mean annual minimum temperature in four climate models: CGCM2- A2, CGCM2-B2, ECHAM4-A2, and ECHAM4-B2. For each variable, the different values simulated for Sierra Nevada were analysed for the years 2011-2100 in each of the different climate models used.

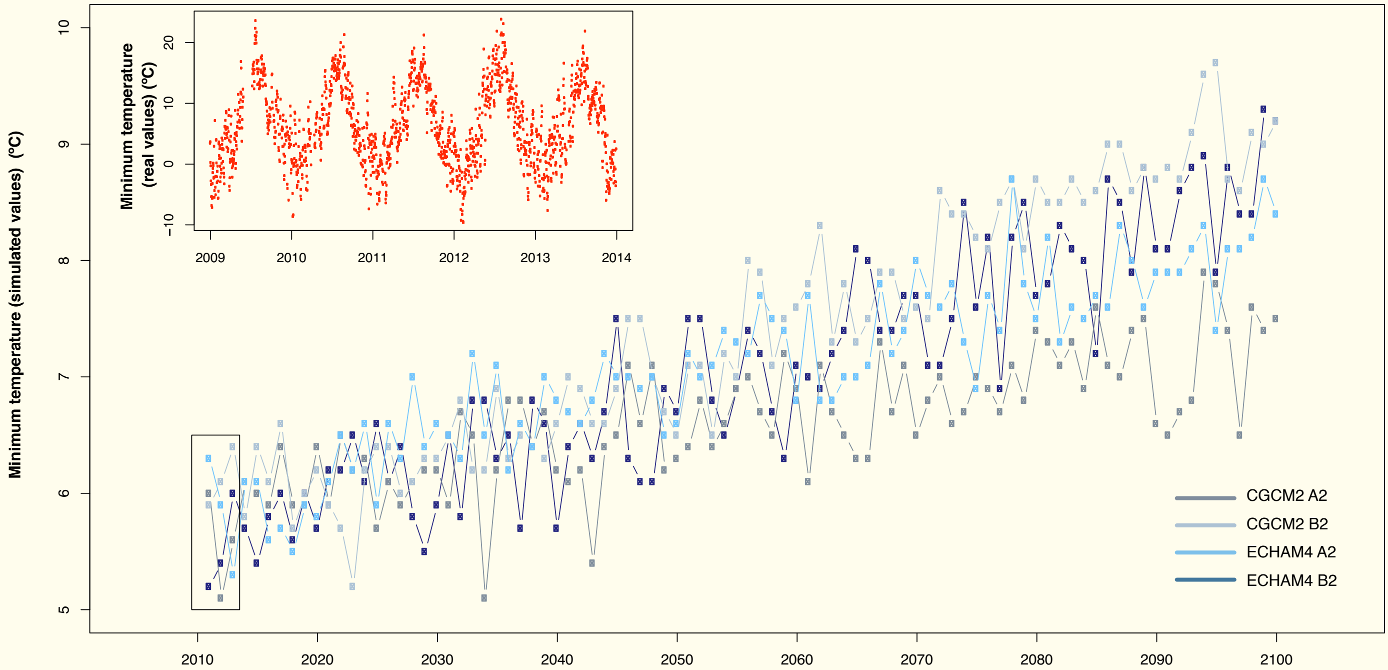
The results of the simulations for each variable were compared with the real values recorded for the extensive network of multiparametric stations that the Sierra Nevada Global Change Observatory between 600 and 3100 m.a.s.l. in the main ecosystems of Sierra Nevada [6] (Figure 1). Specifically for each variable (annual precipitation, annual averages of the maximun temperatures and of the minimun tempertatures) the correlations were analysed comparing the values provided by the simulations against the real values for the period 2011-2013. For this, the simulated values were used for each of the pixels that coincided with the location of the multiparametric stations.

Table 1

		Temperature change (ºC at 2090-2099 relative to 1980-1999)	
Scenario	**CO2 (ppm) concentration**	**Best estimate**	**Likely range**
Ref. (2000)	365	0.6	0.3 - 0.9
B2	800	2.4	1.4 - 3.8
A2	1,250	3.4	2.0 - 5.4

Main characteristics of the emission scenarios A2 and B2 (Source IPCC).

Figure 1



Temporal evolution of the mean annual minimum temperatures for the multiparametric station of Cañar, showing the values simulated according to the four climate models considered. The upper frame presents the values of the minimum daily temperatures registered by the multiparametric station for the period 2009-2014.

Results

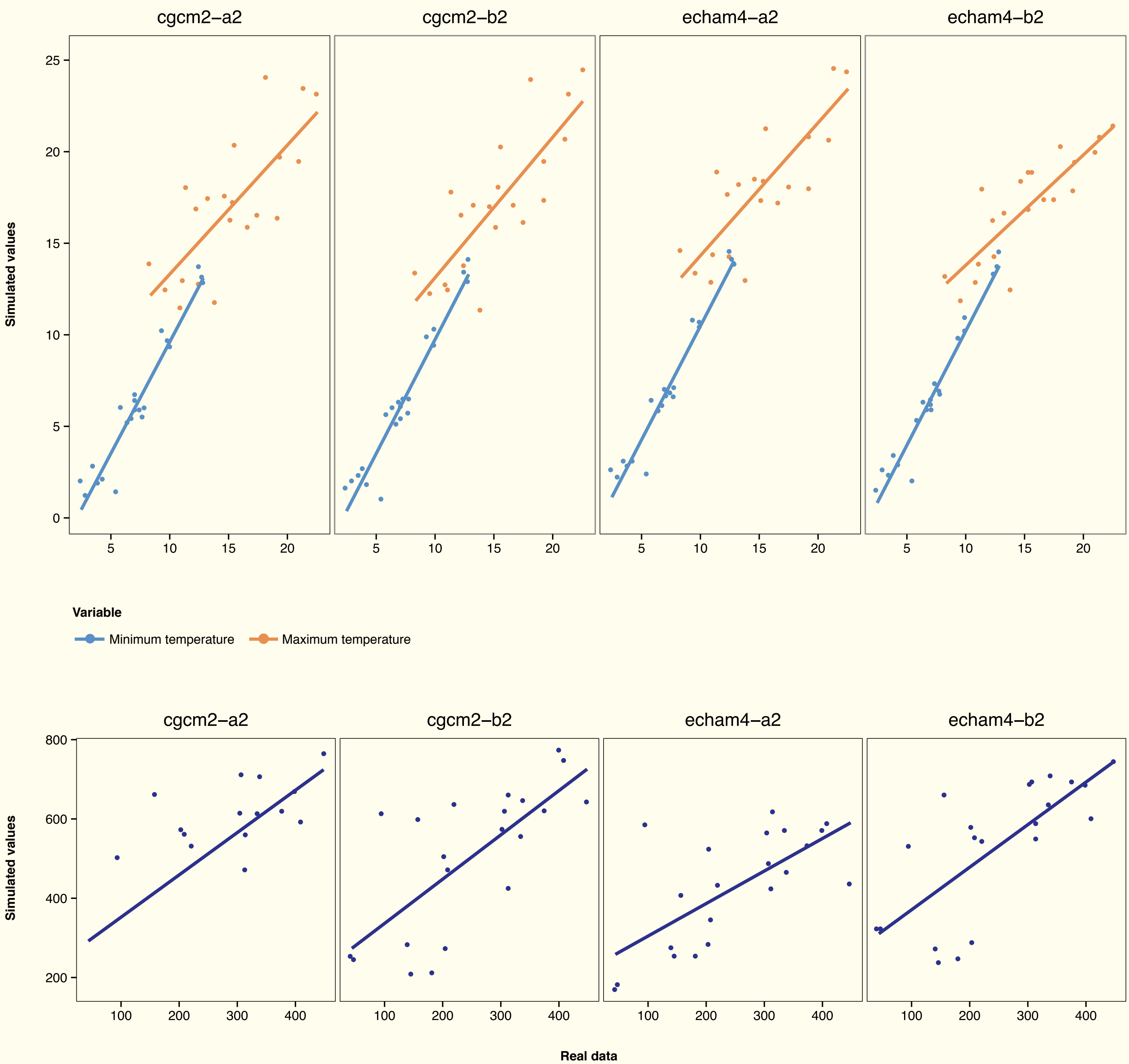
The results of the climate simulations for the future in Sierra Nevada according to the four climate scenarios show an increase in temperatures and a decrease in precipitation. Maximum temperature is expected to rise between +2.56 °C and +6.22 °C depending on the model and scenario (Table 2). For minimum temperatures, this rise is expected to range from +1.81 °C to +4.38 °C.

Table 2

Variable	Model	Scenario	Average difference 2100-2011
Precipitation	CGCM2	A2 B2	-112.60 ± 44.14 52.32 ± 41.56
	ECHAM4	A2 B2	-38.32 ± 31.42 -89.91 ± 31.31
Maximum temperature	CGCM2	A2 B2	6.22 ± 0.47 2.56 ± 0.21
	ECHAM4	A2 B2	4.98 ± 0.68 3.36 ± 0.27
Minimum temperature	CGCM2	A2 B2	4.38 ± 0.83 1.81 ± 0.46
	ECHAM4	A2 B2	3.79 ± 0.61 2.37 ± 0.39

Average difference in the simulated climatic variables for the entire Sierra Nevada during the years 2011 to 2100 in each of the models of global circulation and the emissions scenarios. The mean and standard deviation are shown. Precipitation in mm and temperature in °C.

Figure 2



Comparison of simulated values from the projections vs. values registered by the multiparametric stations for the years 2011-2013. Upper panel, mean maximum and minimum temperatures; lower panel, annual precipitation. The comparisons for the four scenarios are shown.

The comparison of the real values registered with the multiparametric stations against those simulated in the four climatic scenarios showed high correlation values for the variable temperature but more moderate for precipitation (Table 3, Figure 2). In all cases, for the period evaluated (2011-2013), the scenario that best predicted the real values in Sierra Nevada was the model ECHAM and the emissions scenario B2, since these showed a stronger correlation for the three variables.

Table 3

Variable	Model	Scenario	R^2
Precipitation	CGCM2	A2 B2	0.526 0.519
	ECHAM4	A2 B2	0.467 0.546
Maximum temperature	CGCM2	A2 B2	0.573 0.651
	ECHAM4	A2 B2	0.628 0.710
Minimum temperature	CGCM2	A2 B2	0.934 0.936
	ECHAM4	A2 B2	0.954 0.961

Results of the correlations between the climate simulations and the real values for the multiparametric stations for the period 2011-2013. The data of 7 stations were used, excluding the station at Veleta for its discontinuity in the data series.

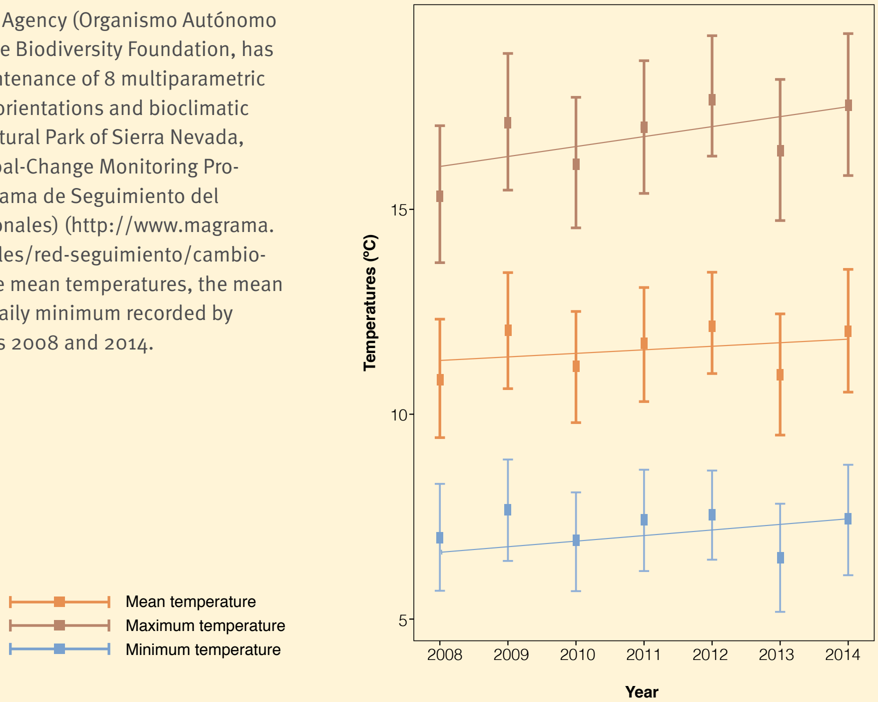
Discussion and conclusions

The climate simulations for Sierra Nevada projected higher maximum and minimum temperatures, with the A2 scenario giving the most severe projections. These results are similar to those generated with regional models for Sierra Nevada [7]. In this sense, the rise in minimum and maximum temperatures found for the A2 scenario are within the interval of values offered by projections made with different models for the Iberian Peninsula [8-10], which indicate increases of up to 6°C and 8°C by the end of the century for mean annual minimum and maximum temperatures, respectively.
The values simulated with the future climate maps for Sierra Nevada, which point to rising temperatures, as projected in other works, reflects that the maps generated are consistent with the potential trends estimated for the Iberian Peninsula [8].

On the other hand, high correlations have been detected between the values predicted by the simulations and the real values from multiparametric stations. Although only three years were evaluated, the results show that the simulations projected for the B2 scenarios are the most probable ones, since in all of them the variables are the ones correlating best with the real data (Table 3). The correlation values found indicate that for these three years, the simulations accurately predict the temperature values found, regardless of elevation. On the other hand, lower correlation values were registered for precipitation than for temperature, supporting the idea that the simulations made for the first variable are more trustworthy [8].

With respect to the simulations for precipitation, a differential pattern was found depending on the model. This finding can be explained by the high degree of uncertainty in the precipitation simulations due to both the techniques of spatial regionalization as well as techniques of regionalization of atmospheric dynamics, as mentioned in other studies in the Iberian Peninsula [9]. This uncertainty is particularly aggravated in areas with high topographic gradients such as Sierra Nevada, for which the precipitation simulations should be interpreted with caution. Nevertheless, the models predict a reduction in precipitation at the end of the 21st century, this forecast being supported by findings in other works that also demonstrate a reduction of the precipitation in the southern half of the Iberian Peninsula by applying different models [8-10].

The National Parks Autonomous Agency (Organismo Autónomo Parques Nacionales), through the Biodiversity Foundation, has funded the installation and maintenance of 8 multiparametric stations distributed in different orientations and bioclimatic belts inside the National and Natural Park of Sierra Nevada, within the framework of the Global-Change Monitoring Programme in National Parks (Programa de Seguimiento del Cambio Global en Parques Nacionales) (http://www.magrama.gob.es/es/red-parques-nacionales/red-seguimiento/cambio-global.aspx). The plot shows the mean temperatures, the mean daily maximum, and the mean daily minimum recorded by these stations between the years 2008 and 2014.



Multiparametric station (Camarate II - Piedra de los Soldados) located at 2155 m.a.s.l.

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› More references at http://refbase.iecolab.es/ref_dossier_resultados.html

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Chapter 2

The summits of Sierra Nevada from La Carihuela.

Snow cover dynamics at the summits of Sierra Nevada

The snow cover, the water layer in its solid state, accumulates from precipitation in the form of snow. Its structure and dynamics can change over the year, shifting from solid to liquid and *vice versa*, depending on the climatic conditions. The water resulting from the snowmelt can percolate through the soil, infiltrating or running off feeding rivers. The peculiarity of this element is that it can also fluctuate markedly in its physico-chemical properties over space and time.
For the above characteristics, snow is a key element in mountain ecosystems. On the other hand, its weight and its thermal conductivity contribute to its function in many ecological processes (water supply, buffering the negative effects of cold temperature, etc.). Thus, in places where snow is frequent, the hydrological pattern differs from those where no snow forms. In addition, at these sites, the snow determines the distribution and structure of plant communities.

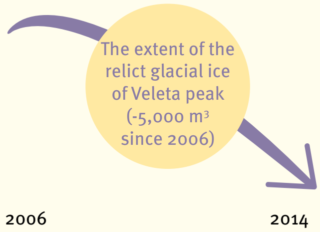
The snow cover is therefore a fundamental physical element in order to understand several processes in mountain ecosystems. This role becomes even more important in the current context of global change. The climate change scenarios forecast major changes in the abundance and distribution of precipitation. These changes will thus affect the state and behaviour of the snow cover. In turn, these alterations in the snow cover may provoke changes of varying intensity in mountain ecosystems.

Sierra Nevada, due to its height (3482 m.a.s.l.), is the mountain range in the southern Iberian Peninsula where the snow lasts the longest. The water contained in the snow feeds the forests, shrublands, and aquatic ecosystems, in addition to agriculture and other human activities (livestock, recreational activities, etc.) both in the Sierra Nevada as well as in the surrounding districts.

From the Sierra Nevada Global Change Observatory, an integrated and multi-scale monitoring

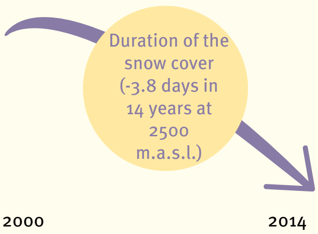
Great spatio-temporal heterogeneity of the snow layer and temperature

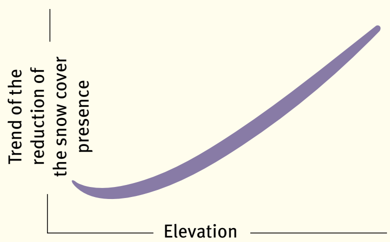
The snow layer can vary four-fold in depth among years



Permafrost

cannot persist in Sierra Nevada under the current climate conditions





The reduction in the duration of the snow

is more intense in May and October

Summary of the main results described in this chapter. The evolution of snow duration and extent of glacier ice for the Veleta summit are shown. The variation in the trend of the snow cover presence over the elevation is included.

system has been implemented to track the characteristics of the snow cover. The most detailed scale consists of *in situ* sampling to evaluate the physical characteristics of the snow and its capacity to store water. These local data are used in combination with other techniques (photographs in the field to evaluate the changes in the surface area) to calibrate and validate the hydrological model WiMMed (Watershed Integrated Model in Mediterranean Environments).

Also at this detailed scale, periodic measurements of the soil temperatures at various depths are made with the aim of evaluating the existence of permafrost in Sierra Nevada. Finally, an extensive monitoring of the snow cover is carried out using satellite images provided by the MODIS sensor.

The data recorded from a snowpit during the years 2011-2013 provide useful information on the behaviour of the snow layer. The most remarkable feature is the great spatial and temporal heterogeneity of the snow cover. The depth of the snow, for instance, can differ four-fold in two consecutive years, depending on the local climate conditions. The information generated from the snowpits has been used to validate the hydrological model WiMMed, which also simulates the extent and quantity of water stored in the snow.

The monitoring of soil temperature in the summit area has enabled an evaluation of the capacity of Sierra Nevada to harbour permafrost. Currently, only in places where soil remains frozen, geomorphological processes can persist (e.g. gelifluction). In addition, a progressive loss of relict glacial ice and permafrost is appreciable in the Corral del Veleta.

The time series analysis from MODIS images from 2000 to 2014 provides informative data on the trends of the snow cover duration, starting date of the snow, and snowmelt date, on a pixel scale of 500 m throughout Sierra Nevada. A clear trend towards a shorter duration of the snow cover was detected. This trend was stronger at higher elevations, and was concentrated in the beginning month (October) and end of the snow season (May). Although these results are consistent with those described in Chapter 1 for the precipitation trend, they cannot be considered conclusive, as the period analysed is not sufficiently long.

The results found help in the understanding of the structure and dynamics of the snow layer in Sierra Nevada. They also contribute to the simulation and evaluation of the effect of snow cover on providing ecosystem services.

2.1. Monitoring the physical characteristics of the snow layer

Algarra, J.A.[1] and Herrero, J.[2]

[1]Environment and Water Agency of Andalusia [2]Andalusian Institute for Earth System Research. University of Granada

Abstract

The presence, distribution, and duration of the snow layer in Sierra Nevada is one of the physical characteristics that make this mountain range such a peculiar spot. This resource serves as the basis for economic activities such as skiing. It is a water reservoir that extends in time and alleviates the scarcity of water in dry summer periods and buffers Mediterranean torrentiality; it modulates ecosystems that bear exclusive and/or relict flora from cold periods. The accurate understanding of its properties, dynamics, and vulnerability to climate change is fundamental for managing and planning all the ecosystem services that it affects [1]. In the present work, periodic *in situ* monitoring campaigns of the snow layer are combined with fixed monitoring stations of the meteorological values that determine its behaviour, a photographic station to make detailed studies of the time course of the surface cover, and the application of all this into a physical modelling of the snow using the software WiMMed [2]. This aids in the forecasting of the behaviour of the snow layer with respect to meteorological predictions or to past and present hypothetical scenarios as well as the effect of this layer on the hydrology of the rivers of Sierra Nevada.

Aims and methodology

The objective is to delve into the physical properties of the snow, its distribution, and its dynamics at different spatial scales in an effort to understand better the real effects of snow on the hydrological cycle and on ecosystems. In addition, the aim is to design tools to forecast the evolution of the snow layer in a context of climate-change scenarios or meteorological events (droughts, cold fronts, etc.). For this purpose, different monitoring methodologies have been combined, such as complete fixed weather stations and video monitoring stations directly over the snow. This monitoring has been complemented with the use of a simulation model of the snow from a physical approximation (WiMMed)[2], enabling the prediction with the support of the *in situ* monitoring work.

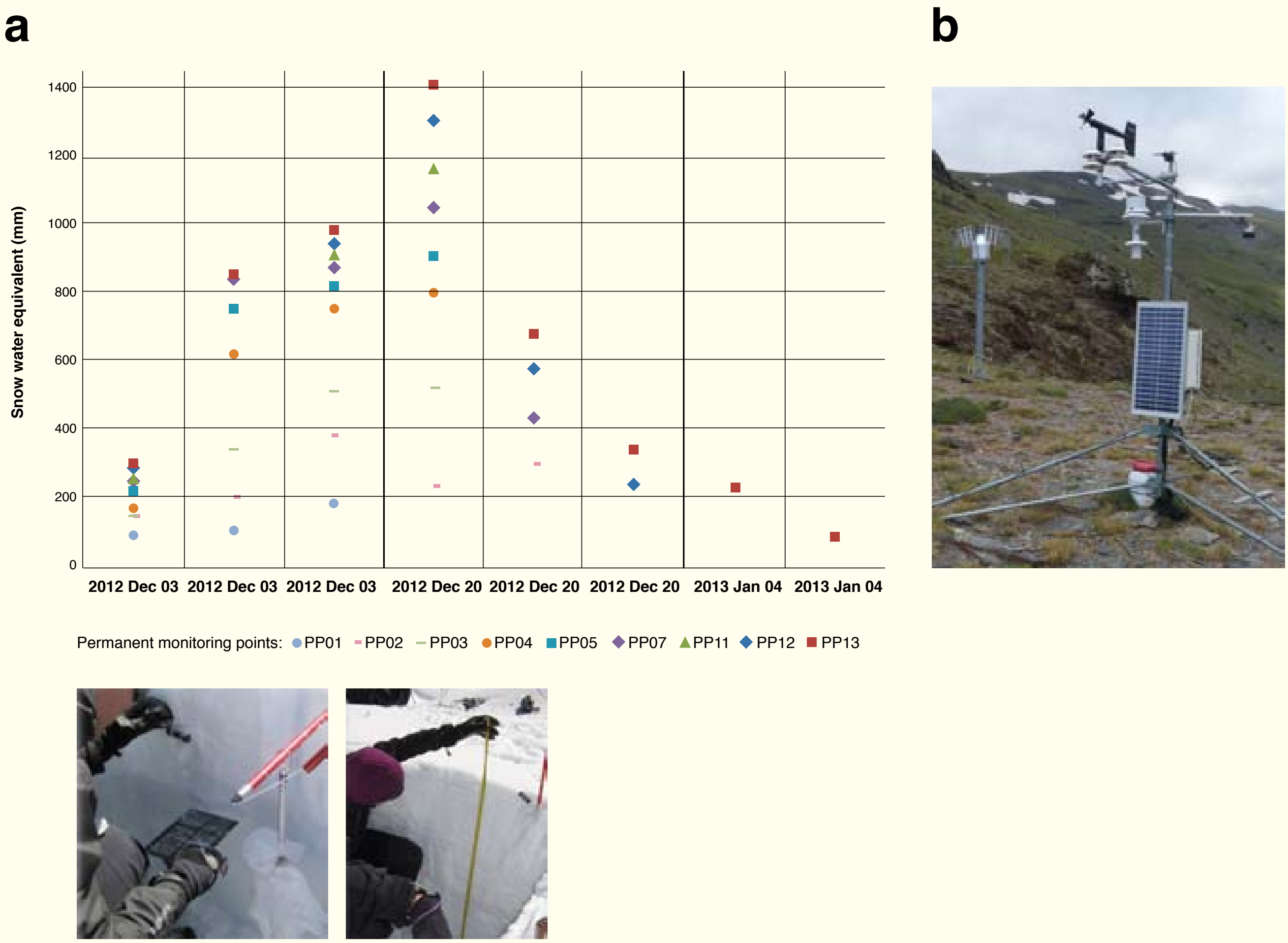
Results

The *in situ* monitoring confirmed the great spatial and temporal variability of the snow layer in Sierra Nevada. Over the study years, a systematic record was made of the values of density, snow water equivalent, thickness, number of layers, and particular properties (hardness, temperature and grain size). This made it possible not only to estimate the quality of the stored snow but also to evaluate the stability of the layer and the risk of avalanches in the most unstable areas.

This is the first time that systematic data on the properties of the snow in Sierra Nevada have been compiled *in situ* [4], and this project extend them to both slopes of the Sierra Nevada. These measurements represent a major point of reference to quantify the time evolution of the snow properties.

The photographic monitoring gave rise to detailed maps of the snow in the high part of the Trevélez river basin, enabling the study of the dynamics of the snow and its behaviour

Figure 1



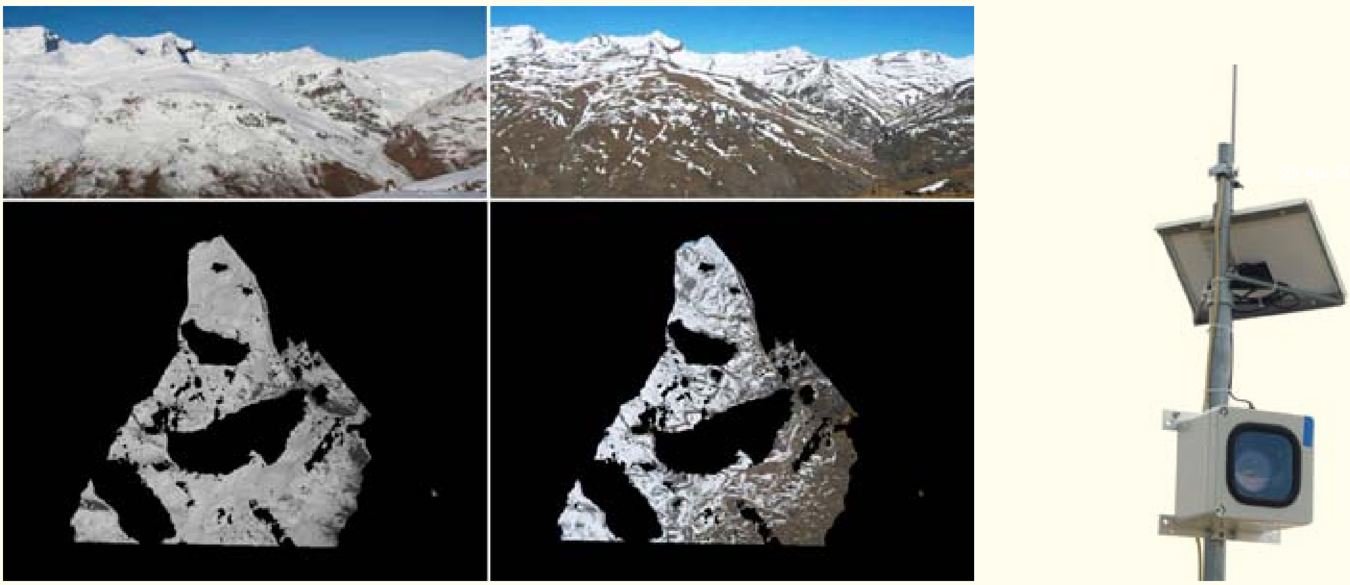
Variation of the snow water equivalents at the permanent monitoring points taken in the same basin (Genil river) from 2012 Dec 03 to 2013 Jan 04 (a). The high variability by date and sampling point was striking. On the right, one of the complete weather stations installed in an area of snow in the Trevélez river valley (b).

in spatial distribution according to elevation and orientation. It was found that, due to the south-eastern orientation of the slope, the snow maintained a rather even distribution, growing in thickness with elevation, which was successfully simulated with WiMMed [3]. A simulation technique was developed for direct assimilation of the data of the surface snow cover depicted by the photograph in the model, improving the prediction of the Trevélez river flow rate.

The weather stations installed enabled not only the monitoring of certain environmental conditions in the high areas of Sierra Nevada, but also the measurement of energy flows that determine the behaviour of the snow layer [4].

Figure 2

a **b**



a) Example images on two different dates after restitution and georeferencing. Source: [3].
b) Camera for snow monitoring in the Trevélez river valley.

Discussion and conclusions

For the *in situ* monitoring, the standard recommendations described [5] were followed but adapted to the peculiarities of the snow on Sierra Nevada. Notable among these are thin layers of snow, except in very particular areas of snow accumulation, and high variability in time and space, with patchy snow and differences between contiguous slopes with different orientations. It bears noting the exceptional accumulation of snow during the 2010-2011 season.

In Mediterranean ecosystems, snow cover a basic determinant of the temporal distribution of water, which is especially scarce in these areas. Water use for irrigation and consumption cannot be effectively planned without knowledge of the evolution of the snow cover.

2.2. Degradation of relict glacial ice and permafrost in Sierra Nevada

Gómez-Ortíz, A.[1]; Salvador-Franch, F. [1]; Oliva-Franganillo, M.[2] and Salvà-Catarineu, M.[1]

[1] University of Barcelona [2] University of Lisbon

Abstract

The remains of relict glacial ice and *permafrost* that remain under layers of clasts in the Corral del Veleta, in the eastern third of its base, constitute heritage of the Little Ice Age. These frozen bodies coming from the small glacier that overflowed the basin of the Corral, as it is evidenced at several historical documents from the 17th to the middle of the 20th century. Currently, they are in the process of steady deglaciation.

Aims and methodology

The central aim is to analyse and explain the degradation process of the relict glacial ice and *permafrost* of the Corral del Veleta (3150 m.a.s.l.) [6]. The methodology and techniques consisted of monitoring the behaviour of the parameters involved in this process in order to ascertain:

a) the snow layer in summer, from digital photographs appropriately corrected;

b) the movement of the clast layer, from geomatic techniques;

c) the temperature of the active layer, from thermal sensors (*data-logger type*);

d) and the physical state of frozen bodies, from geological surveys (tomography). The monitoring began in 2001 in a sampling zone corresponding to the incipient rocky glacier next to the small lake of the Corral del Veleta with a surface area of 3815 m². The parameters a, b, and c were monitored annually during the last week of August. Parameter d was monitored in August of 1999 and 2009.

Results

The monitoring methodologies applied to evaluate the physical state of the relict glacial ice and permafrost provide conclusive data of progressive degradation. In this sense, the information in Table 1 is significant for the period 2006-2013. Over this period, the underlying ice mass could shed a volume of 5001.3 m³, mostly in the form of water [8]. This quantity is distributed unevenly in time but proves to be closely related to the collapses of the detrital layer -1.311 m (Table 1). The lack of information for the years 2009-2010, 2010-2011, and 2012-2013 is due to the extent and thickness of the snow on the ground in August, which prevented the recording of other monitoring data.

Table 1

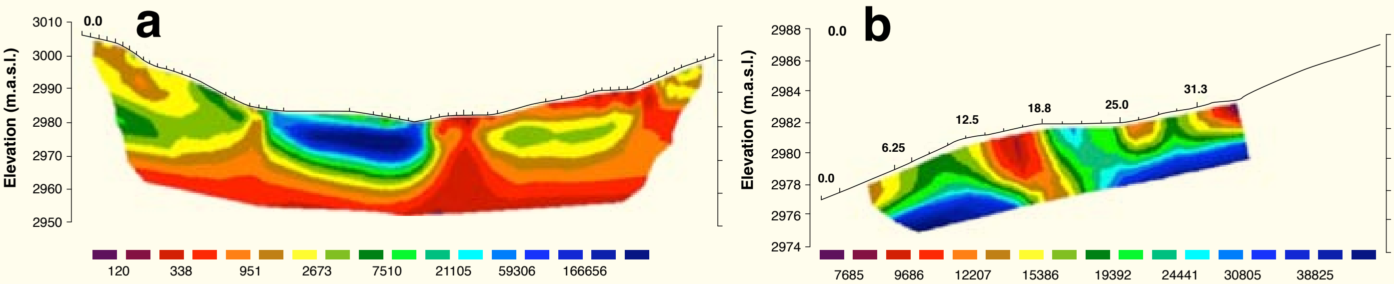
Period	Subsidence/collapse (m)	Volume loss (m³)
2006-2007	-0.401	1,529.82
2007-2008	-0.391	1,491.6
2008-2009	-0.240	915.6
2009-2010	sd.	sd.
2010-2011	sd.	sd.
2011-2012	-0.279	1,064.3
2012-2013	sd.	sd.
Total	**-1.311**	**5,001.3**

Data on the collapse and loss of water per year wd.: without data for being covered again by snow during the monitoring.

With respect to the distribution of the relict glacial ice and permafrost on the monitored surface (3815 m^2), the electrical tomography used in 2009 (Figure 1) indicates that the top of these ice bodies have at least -2 m distributed irregularly in compartmentalized hollows, as indicated by the values of maximum resistivity, as opposed to what was detected in the 1999 record, which then made up continuous packages.

Figure 1

Eastern sector at the bottom of the Corral del Veleta. Study area.



Electrical tomography in August 2009 by J. Galindo Zaldivar).
a. Vertical section of segment a.
b. Vertical section of segment b.
The blue tones correspond to the greatest resistivity (frozen bodies).

› Discussion and conclusions

The degradation process of the relict glacial ice and permafrost of Corral de Veleta is interpreted as resulting from a cascade of physical processes, beginning with external radiation that strikes the ground and melts the snow. The progressive elimination of the snow in summer encourages the external energy to progressively penetrate the active layer of the soil, generating positive temperatures throughout the profile, reaching the top of the glacial ice and permafrost, which degrades and melts. Throughout this process, the circulation of the waters from the melt plays a major role in the transmission of heat. This explains the subsidence and continuous readjustment of the entire clastic layer as well as the melting of the top of the ice that had settled there [7]. The magnitude of the collapses and the losses of glacial ice and permafrost is invariably greater in years when the snow disappears early, as occurred during the period 2006-2007. On the contrary, this is less when the snow lasts to the end of the summer, as happened in a pronounced way during the years 2009-2010 and 2010-2011, when the positive temperatures did not succeed in reaching the top of the relict glacial ice or permafrost. In this sense, the record for 2011-2012, which offers values of -0.279 m of collapse and 1064.3 m^3 of loss of ice bodies, clearly reflects these events, if it is taken into account that they correspond to a time interval of 36 months (from August 2009 to August 2012). All these physical processes described indicate that it is the permanence of the snow (and its thickness) in summer that controls the pace and magnitude of the degradation of the relict glacial ice and permafrost [8].

2.3. Thermal regime of the soil

Salvador-Franch, F.[1]; Oliva-Franganillo, M.[2]; Salvá-Catarineu, M.[1] and Gómez-Ortiz, A.[1]

[1] University of Barcelona [2] University of Lisbon

Abstract

The monitoring of soil temperature at different points of Sierra Nevada and at different depths help to explain the dynamics of permanent and seasonal frozen ground. At present, the records show a degradation in the residual ice masses in the Corral del Veleta. There is also evidence for the current absence of permafrost conditions in the summits. Finally, an annual pattern appears in the behaviour of soil temperature, determined by the presence/absence of snow.

Aims and methodology

The observation of the thermal characteristics of the soil began in Sierra Nevada as a method of detecting and monitoring the permanent frozen ground (*permafrost*) and as support for better knowledge of periglacial morphodynamics, for which contrasting morphotopographic enclaves of the highest sector of Sierra Nevada were equipped with instruments [9], as indicated in Table 1. This line of research received decisive impetus during the development of the project PACE (*Permafrost and Climate in Europe, 2008-2010*), in which Sierra Nevada represented a key site to serve as the southernmost observation point of a long transect that reached Svalbard (Norway). For the thermal monitoring of the air and the soil, different generations of autonomous data loggers were used (TinyTalk II, de Gemini; UTL 1 y 2, de Geotest; Hobo U12 y Pendant, de Onset; iButton) with the capacity for data storage of 1-3 years and measurement frequencies of between 4 and 1 h [9].

Table 1

Site	Elevation	Slope	Preliminary observations	Continuous series	Sampling levels
Albergue Universitario	2510	N	---	2008-under way	air / soil: -5, -20, -50, -80 cm
San Juan	2864	N	---	2003-2012	soil: -2, -10, -20, -50, -100 cm
Corral del Veleta	3107	N	1997-1999	1999-under way	soil: -5, -20, -50, -100, -150 cm
Collado de los Machos	3297	crest	1999-2000	2003-under way	soil: -5, -20, -50, -80 cm
Picacho del Veleta	3380	crest	2000-2002	2002-under way	air / soil: 11 levels, between -20 cm and -60 m
Pandero del Mulhacén	3200	S	1999-2000	---	soil: -5, -10, -50 cm
Río Seco	3105	S	---	2006-2012	soil: -2, -10, -20, -50, -100 cm

Summary of sites, series, and levels of thermal observation.

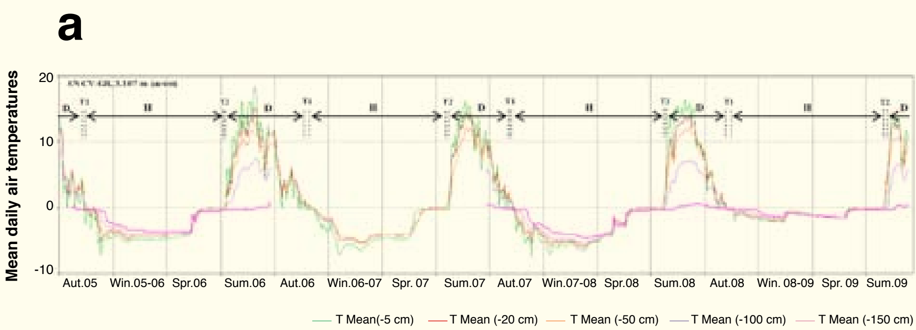
Results

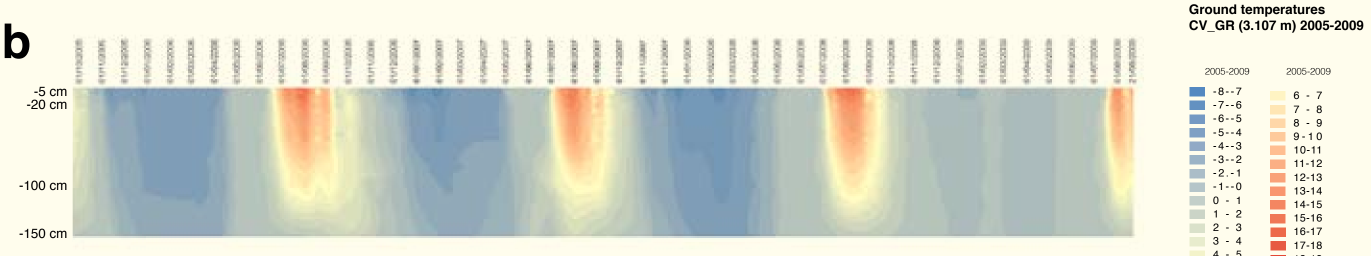
The thermal monitoring undertaken has helped to determine the causes for the degradation of the ice masses and residual *permafrost* in Corral de Veleta, as well as the dynamics of glacial bedrock [10-11]. On the other hand, the current absence of permafrost conditions over the bedrock, superficial formation, and soil in the summit sector have been confirmed. In the bottoms of the valley of the old glacial cirques of San Juan and Río Seco, the current dynamism of the gelifluction lobes has been related to its precise thermal determinants [12]. On Machos hill, current thermal conditions are incapable of maintaining the dynamism of the geometric macrofigures existing there [13]. In all cases, a distinct annual pattern was detected in the thermal regime of the soil clearly determined by the presence/absence of snow, with prolonged periods of freezing (H), shorter thaw periods (D) and other very short transition periods (T1, T2) between the freeze and thaw periods (Figure 1) [11]. Also striking were the data in relation to the sharp reduction in the number of freeze-thaw cycles, in the thermal amplitude, and in the extreme thermal values affecting the soil in comparison with those recorded for the air.

Discussion and conclusions

The works on thermometry in the summits of Sierra Nevada reflect the value of monitoring air and soil temperatures and of having a sufficiently long-term series in order to understand more precisely the current morphobiological functioning and dynamics of high-mountain environments as well as their direct relationship with the behaviour of the snow layer. This is of enormous interest with respect to the possibility of the current climate change or variability.

Figure 1





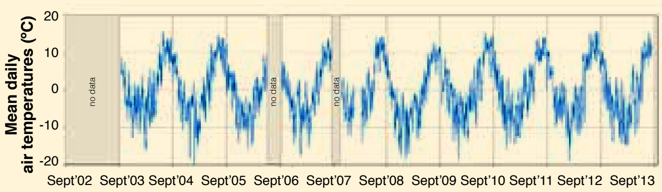
Example of the thermal behaviour of the soil at Corral del Veleta at 150 cm deep.

Thermometry of the substrate of Veleta Peak

The prevailing geomorphological dynamics in the Sierra Nevada summits are governed by a soil thermal regime characteristic of the periglacial environment with seasonal soil freezes without the *permafrost*.

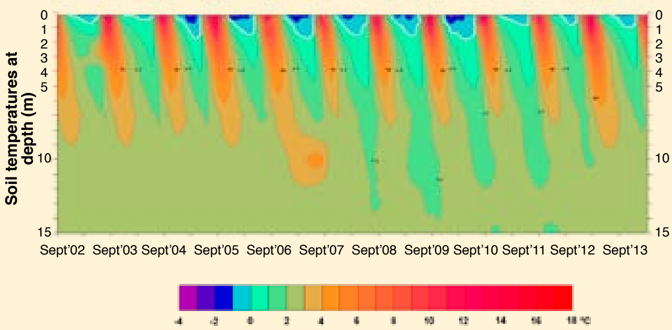
Currently in Sierra Nevada the thermal conditions of *permafrost* have been recorded only in the core area of the highest northern cirques, particularly in the Corral de Veleta. Since the year 2000, the thermal conditions of the substrate and air have been monitored at Veleta Peak. For the substrate, data have been taken from the uppermost 60 m with thermorecorders at intervals of 2 h at different depths (0.2; 0.6; 0.8; 1.2; 2.6; 4.0; 7.0; 10.0; 13.0; 15.0; 20.0, and 60.0 m.) while, for the air, temperature monitoring was conducted at a flagpole near the peak of Veleta (3398 m.a.s.l.; Figure 1).
The results (August 2002 – August 2013) show mean temperatures in the interior of the rock that stabilize at around 2.5 °C in depth [14]. The data indicate an alternation between a cold season in which the substrate remains frozen above 0.6 to 2.0 m in depth and a warm season when the values are quite positive (Figure 2). In the study period, the mean air temperature in Veleta rose by 0.12 °C, whereas in the substrate the temperatures followed diverging trends. The thermal diffusivity of the rock was quantified at $7.05 \pm 0.03 \cdot 10^{-7}$ m^2/s, implying that the exterior climatic signal arrived with a lag of 8.5 years in relation to the sensor situated at 60 m in depth.

Figure 1



Daily air temperatures at the Veleta peak between September 2002 and August 2013.

Figure 2



Ground thermal conditions between September 2002 and August 2013.

2.4. Trend analysis (2000-2014) of the snow cover by satellite (MODIS sensor)

Bonet, F.J.; Pérez-Luque, A.J. and Pérez-Pérez, R.
Andalusian Institute for Earth System Research. University of Granada

Abstract

The MODIS sensor carried by the satellite Terra of NASA provides information of the snow cover from the year 2000 to the present. The complete time series of the MOD10A2 product has been analysed for Sierra Nevada. This product shows the maximum surface area occupied by snow in 8-day periods. The results display negative trends in the snow cover duration in 79.05% of the pixels of Sierra Nevada. There is also a trend towards a later snow cover onset date in 68.03% of the pixels. In addition, 80.72% tended towards an early snowmelt. These trends are more evident the higher in elevation.

Aims and methodology

The aim of this work is to analyse the changes in the snow cover of Sierra Nevada from 2000 to 2014, using the information provided by the MODIS sensor carried by the satellite Terra of NASA. The snow cover is a landscape element of fundamental importance in Sierra Nevada as its structure and dynamics largely determine the availability of water both in the rivers as well as in the high-mountain ecosystem. It is also responsible for the structure of the vegetation in Alpine environments. The methodology followed is based on the creation of a work flow that automatically processes all the images of the product MOD10A2 (maximum extension of snow for 8 days) of MODIS [15], to generate indicators of the structure of the snow cover (SCD, snow-cover duration, number of days covered by snow per hydrological year; SCOD, snow-cover onset dates, first date in the hydrological year that the pixel has snow; SCMD, snow-cover melting dates, last date in the hydrological year that the pixel has snow) [16]. Below, time-series analysis is applied to characterise the trends of each of the aforementioned indicators in the 7994 pixels comprising Sierra Nevada. The trend analysis evaluates the intensity (adimensional), magnitude (expressed in days early or late), the sign (early or late) and the degree of statistical significance during the analysed period (14 years). Finally, the spatial pattern of these trends was explored according to elevation.

Results

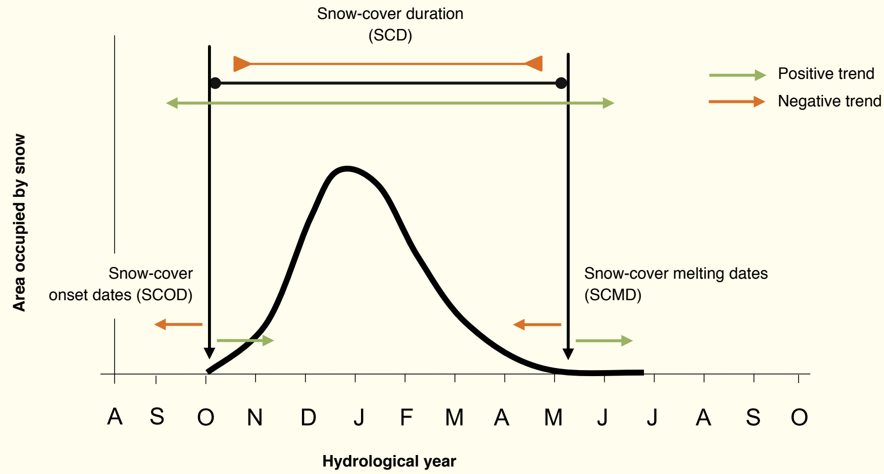
The results show that the snow cover has undergone significant changes in the last 14 years. At the scale of the whole of Sierra Nevada, almost 80% (Table 1) of total pixels showed a negative trend in the duration of the snow cover (see Figure 1 for clarification on the direction of the trends). However, this trend proved significant in only 5.89% of the pixels. The snow-cover onset date showed a similar pattern: 68.03% of the pixels had a positive trend (later starting date). Finally, 80.72% of the pixels followed a negative trend (earlier) for the last date of snow presence.

The values of the trends described above are distributed in the territory following a well-defined spatial pattern. It is clearly visible that both the intensity of the trend (*tau*) and the magnitude (days of change) become more pronounced with elevation. This situation is especially notable in the case of the snow-cover duration (Figure 2). This means that the changes in the structure of the snow cover were most intense in the highest elevations. This spatial pattern is clearly evident in Figure 3, which shows a map with the trends in the duration of the snow cover.

Lastly, the temporal change pattern (on a monthly scale) in the trends of the snow-cover duration on Sierra Nevada were analysed. Although not statistically significant, the results are relevant and consistent with those described above.

Thus, the trends towards a reduction in the duration of snow are more pronounced in the beginning month (October) and the end (May) of the snow period. These results indicate that the snow begins steadily later and the melts earlier in the season. This appears to explain the reduction in the overall duration of the snow described above.

Figure 1



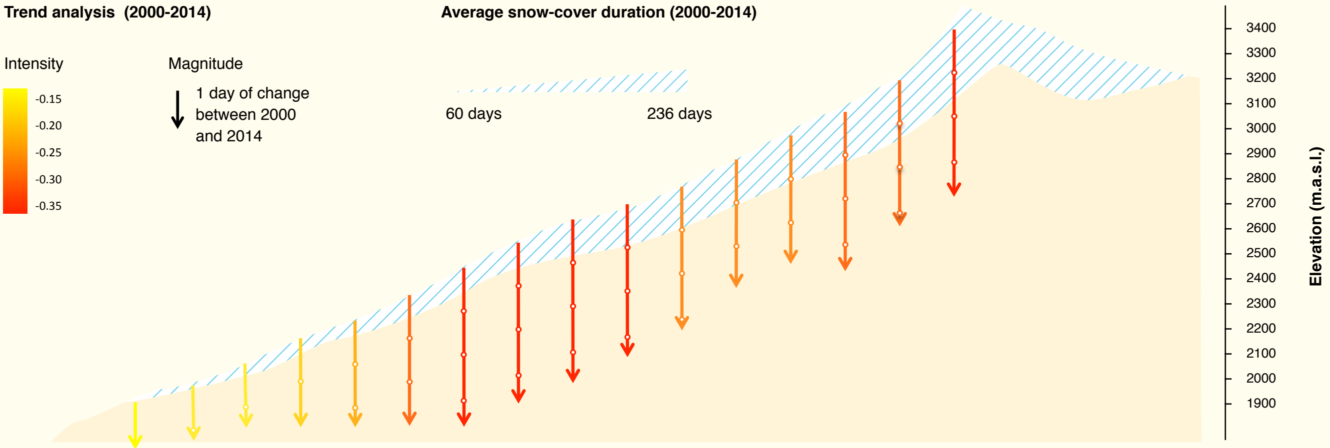
Schematic representing the changes in the surface area occupied by snow over a standard hydrological year. The indicators used to describe the structure of the snow cover are shown. Also, the directions of the trends are indicated. A positive trend in the snow-cover duration implies an increase in this variable. A positive trend in the snow-cover onset date implies a delay in that variable. Positive trends in the snow-cover melting date imply a delay in that variable.

Table 1

		Pixels		Significant pixels	
Variable	**Trend**	***n***	**%**	***n***	**%**
Snow-cover duration (SCD)	Positive Negative	1455 6319	18.2 79.05	6 372	0.41 5.89
Snow-cover onset date (SCOD)	Positive Negative	5438 2380	68.03 29.77	332 59	6.11 2.48
Snow-cover melting date (SCMD)	Positive Negative	1326 6453	16.59 80.72	5 717	0.38 11.11

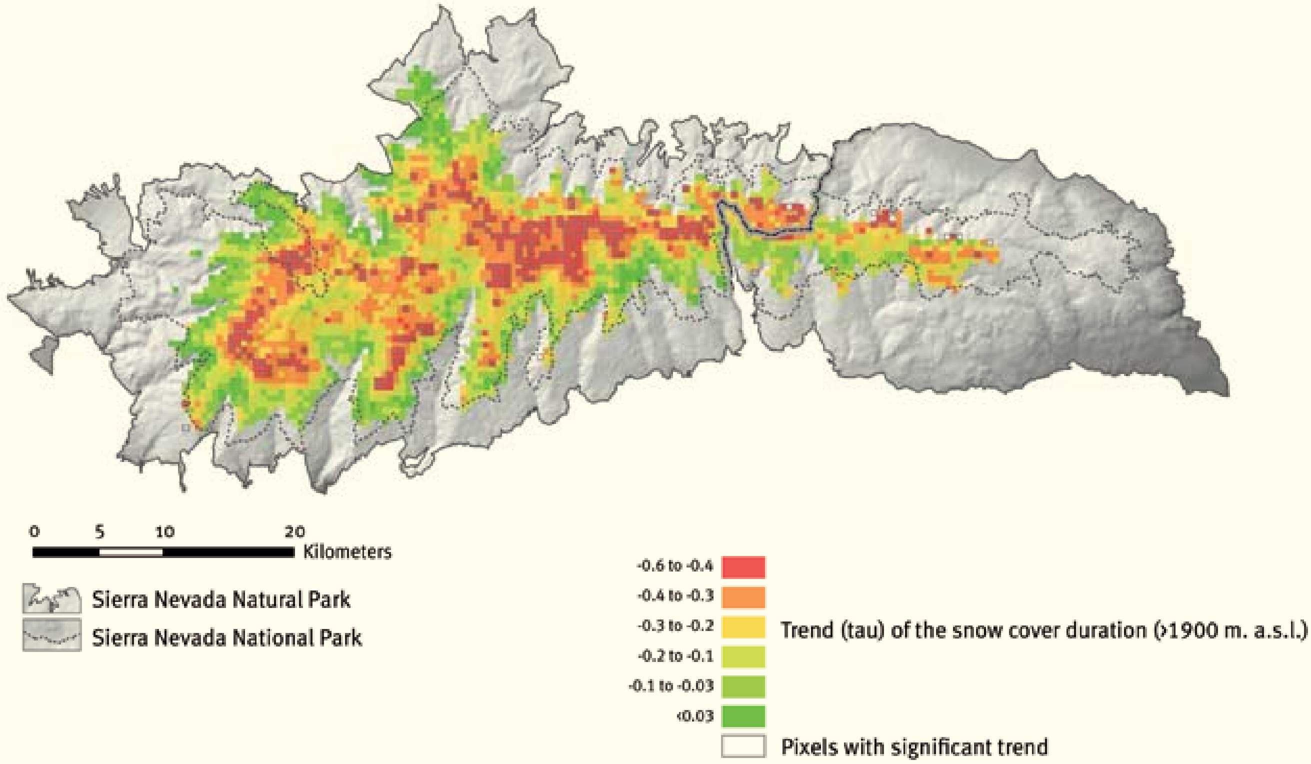
Results of the analysis of the annual trends (Mann-Kendall test) over the last 14 years for the snow-cover duration, the snow-cover onset dates and snow-cover melting dates. For each variable, the number of pixels (n) with negative trends ($\tau < 0$) and positive ones ($\tau > 0$) is shown as well as the number of significant pixels (p-value < 0.05).

Figure 2



Graphic representation of the changes in intensity (*tau*) and in magnitude (slope) of the trend observed for the snow-cover duration in the different elevational ranges (from 1900 to 3500 m.a.s.l.). The colours of the arrows indicate the intensity of the trend in the snow-cover duration (*tau*). The lengths of the arrows located at each elevation indicate the magnitude (expressed in days) of each trend. For instance, in the range of greater elevation, an average magnitude of -3 days was found. This means that the snow-cover duration was reduced in 3 days in the last 14 years.

Figure 3



Map of the trend in snow-cover duration in Sierra Nevada (elevation › 1900 m.a.s.l.). The significant pixels are represented with dark outlines.

Discussion and conclusions

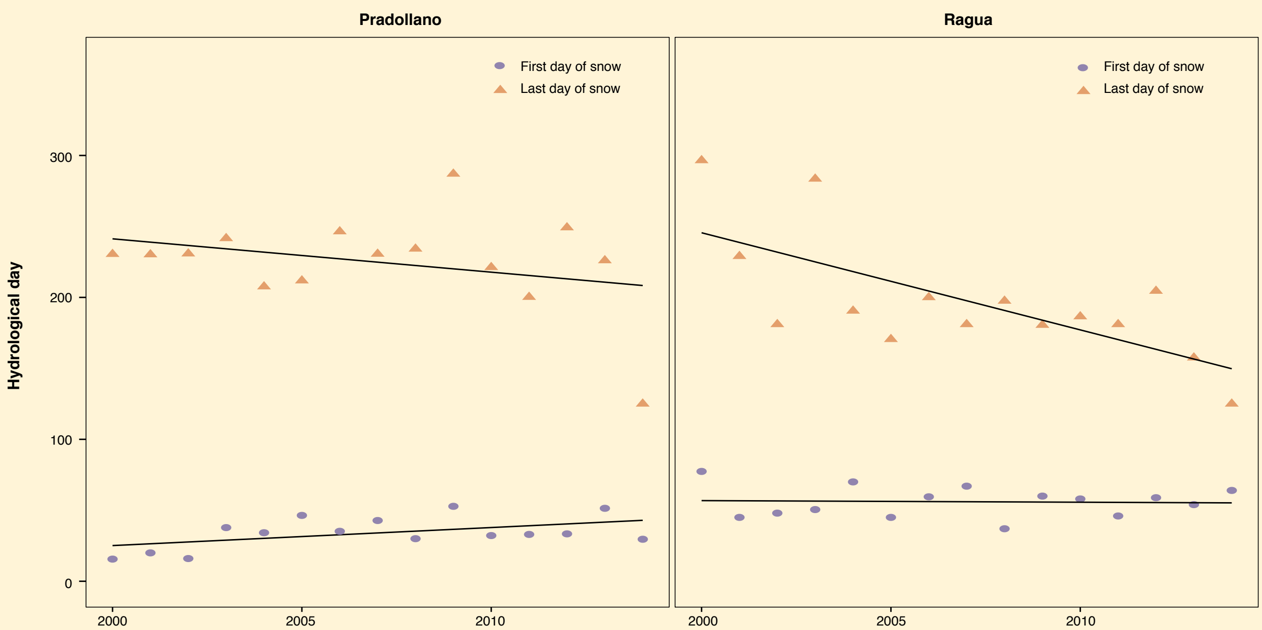
Although the time series considered is not very long (14 years), the trends observed provide preliminary information on the changes that may be occurring in the snow cover of Sierra Nevada. In any case, decreased trend in the snow-cover duration in Sierra Nevada is consistent with that reported in the Alps [17]. However, in other mountains (Central Asia), no such apparent trends have been detected in the same time period as in the present study [18]. This could indicate that the causes of the trends detected are related to local or regional factors, such as the NAO (*North Atlantic Oscillation*) [19].

The trend observed in the snow-cover duration changed over the elevational gradient: the highest areas had more intense trends and greater magnitude towards the reduction of the duration of the snow. This coincides partially with data for precipitation on Sierra Nevada (see Chapter 1) and with other similar studies made in the Alps [17]. The aforementioned gradient of increasing trend intensity with elevation was found also in the annual maximum temperature (see Chapter 1). The link between the the trends of snow-cover duration, the quantity of precipitation, and the annual maximum temperature confirms the causal relationship between climate and snow cover. This relationship is especially important in Mediterranean environments, where a large part of the precipitation falls in spring and winter, and thus the probabilities of precipitation falling in the form of snow are greater.

In short, the time series of the MODIS sensor offers detailed information on the structural and functional behaviour of the snow cover at different spatial and temporal scales. This is of broad interest, given the role of the snow as a provider of ecosystem services.

Trends in the snow cover and ecosystem services

The snow cover constitutes a crucial physical element that determines the structure of the landscape and also the functioning of mountain ecosystems. Furthermore, it serves as a key element for certain economic activities, e.g. snow sports. This reflects the importance of evaluating the potential impact of climate change on the development of this activity. The two figures below describe the trends found in the snow-cover duration, both at the ski resort of Pradollano as well as in that of Puerto de la Ragua. The time course of the first day of snow (circles) and the last day of snow (triangles) are shown for each hydrological year of the series 2000-2014.



Graphs showing the trends on the first and last presence of snow at the ski resort of Pradollano (left) and of Puerto de la Ragua (right), respectively.

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› *More references at http://refbase.iecolab.es/ref_dossier_resultados.html*

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Chapter 3

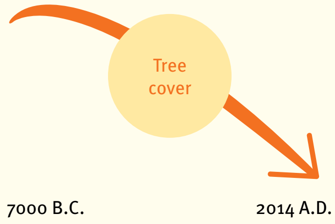
View of Trevélez 1940

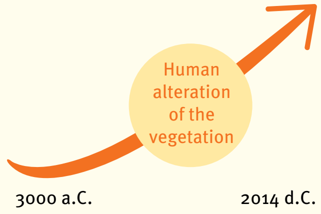
Land-use changes and shifts in vegetation cover

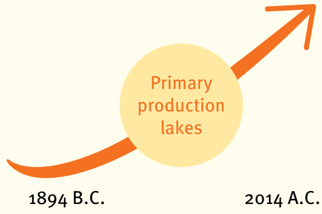
Land-use changes constitutes one of the main drivers of global change. The impact on ecosystem functioning becomes evident: loss of biomass after deforestation, changes in the soil fertility, etc. Delayed effects of land-use change have also been cited regarding ecosystem dynamics: the alteration of species composition of the forests as a consequence of their historical management, the differential regeneration rate of trees according to uses in the past, etc.. This knowledge make the past uses relevant in order to understand the current and future dynamics (Figure 1). Thus, the reconstruction of the past constitutes a key for distinguishing between natural and human causes of global change.

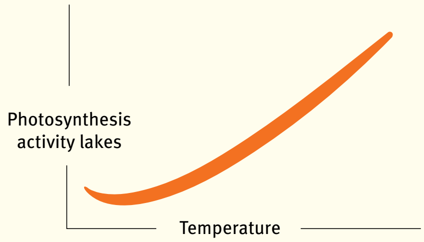
Human activity in Sierra Nevada has for centuries provoked changes in the structure of the landscape. For example, in the last 50 years, land-use change has affected more than half of the 170,000 ha of the protected area. This makes the retrospective characterization of land-use changes a major aim of the monitoring programme.

We have compiled long-time series of the land-use changes in Sierra Nevada, from thousands of years ago until the present. In this sense, we highlight works that reconstruct the vegetation by palynology, enabling us to ascertain the relative abundance of plant species since the last glacial period.



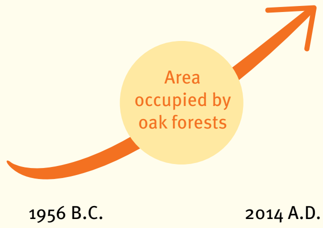


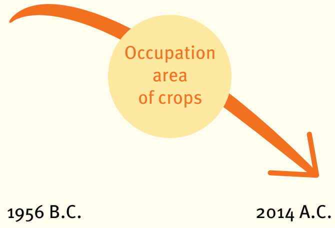




42%

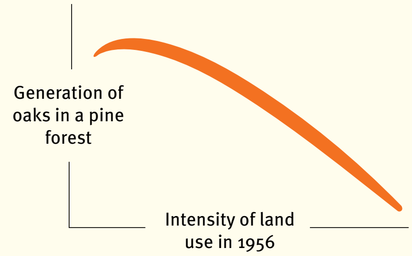
of the area of Sierra Nevada has undergone changes in vegetation since 1956





3.000Km

of irrigation channels (digitalized) that are a key element of the water cycle of the mountain



Progressive aridification is perceptible during the last 7,000 years, with signs of a gradual increase in human activity for the last 3,000 years. Rising temperatures and growing aridity also become evident in the palaeolimnological indicators of the lakes. The analysis of the chlorophyll a content of these lakes reveals an ascending trend quite well correlated with the temperature data compiled for the last 120 years. Furthermore, the compilation of historical information (paintings, forestry maps, land registry, etc.), has made it possible to reconstruct in certain detail the vegetation in particular zones of the Sierra Nevada in the last 100 years. These results reflect a clear process of reforestation of the mountain due both to the abandonment of agroforest-pastures as well as active restoration (pine plantations). This reforestation has reduced the agricultural uses of Sierra Nevada, which have been relegated to the low parts near urban centres. A good part of the structure of land uses in Sierra Nevada in the last few centuries can be defined by a dense network of irrigation channels which are described in detail in this chapter.

Another set of results derive from a study case that quantifies the impact still exerted by the land use of 1956 on a fundamental ecological function for Mediterranean ecosystems: the regeneration of Holm oak forests. We have observed that oak forest regeneration in pine plantations depends largely on land-use legacies. More intense land uses in the past meant fewer biological legacies and, therefore, lower likelihood of regenerating native forest. All the results presented in this chapter have direct applications in the management of the territory.

3.1. Reconstruction of the vegetation from palynological analysis

Jiménez-Moreno, G.
University of Granada

Abstract

The study of the sedimentary pollen record for the last 11,500 years from lakes and bogs of Sierra Nevada indicate maximum temperatures and moisture between 10,500 and 7,000 years ago. This is deduced from the abundance of tree species (especially *Pinus* and *Quercus* and in lesser proportions *Betula*) in Sierra Nevada and the abundance of algae (*Pediastrum, Botryococcus*) in the alpine wetlands. Some 7,000 years ago, progressive aridification began, diminishing tree species and increasing xerophilous herbs (e.g. *Artemisia*, Amaranthaceae). This aridification process was interrupted by climatic oscillations, including several periods of severe droughts (e.g. the Medieval period) alternating with wet periods (e.g. the Roman period). Severe human impact became evident in Sierra Nevada some 3,000 years ago through pasturing and eutrophication of certain wetlands as well as the recent massive cultivation of olive (since 1900 A.D.) at the lowest elevations and pine reforestation elsewhere (since the 1950s).

Aims and Methodology

The pollen grains of the sedimentary record for the last 11,500 years have been studied in different lakes and bogs of Sierra Nevada. In each sediment sample, pollen grains were identified with the use of a light microscope (400x) to the level of family or genus. The grains were classified by comparisons with a current pollen collection and different atlases. The abundance values of the different species were transformed to percentages with respect to the total (without including aquatic species; e.g. Cyperaceae). The pollen diagrams were zoned from a cluster analysis using the software CONISS. The percentage of algae was calculated with respect to the total sum of pollen grains.

Results

Holocene general trends.

11,500 – 10,500 years. The pollen spectra of Laguna de Río Seco are characterized by the abundance of *Artemisia, Ephedra*, and Amaranthaceae, and in lesser proportions Poaceae, *Juniperus*, *Salix*, *Herniaria*, and *Silene* types (Figure 1). *Botryococcus* reached the highest percentages of the entire record.
10,500 – 7,000 years. Both in the lake Laguna Río Seca as well as in the bogs Borreguiles de la Virgen (Figures 1 and 2), maximum percentages were reached by tree species, particularly *Pinus* and *Quercus* (deciduous), but also by *Betula*, *Alnus*, and *Salix* [1,2]. On the other hand, *Artemisia*, *Juniperus*, and Amaranthaceae registered the lowest percentages. The aquatic species, such as *Botryococcus*, *Pediastrum*, and Cyperaceae peaked during this period.
7,000 –5,000 years. *Pinus* remained abundant, but other forest species such as deciduous *Quercus* and *Betula* decreased. The aquatic species also diminished considerably.
5,000 – 3,000 years. *Pinus* progressively declined (Figure 3) whereas *Artemisia* and Amarathaceae increased.
3,000 – present. *Pinus* continued to diminish until c. 1950, when both Laguna de Río Seco and the Borreguiles de la Virgen registered considerable increases. *Artemisia* and *Amaranthaceae* also continued to prosper. *Sporormiella*, a fungus associated with herbivore faeces, augmented measurably both in the record of Río Seco (last 3,000 years) as well in the Borreguiles de la Virgen (last 200 years). The abundance of tecamoebas (Protozoa, Rhizopoda) in Borreguiles de la Virgen in the last 200 years signifies eutrophication [2].

Changes in the vegetation at the millennium scale.

Apart from the general trend towards the decline in tree species in the last 7,000 years, sharp cyclic variations have appeared in pollen abundance, especially in *Pinus* and *Quercus*. In the sequences of Río Seco and Borreguiles de la Virgen, minimum values were found for oaks (both deciduous and evergreen) between 3800-3100 and 1800-600 BP (Figure 4).

Discussion and conclusions

Deglaciation in Sierra Nevada (11,500 – 10,500 years ago)

The oldest sedimentary record for Laguna de Río Seco indicates a steppe-type vegetation (*Artemisia*, Amaranthaceae, *Ephedra*), this being associated with colder and more arid conditions. Similar data for pollen have been recorded in the peat bog of Padul [4], in the cave of Carihuela [5], and in the Alborán Sea.

Early warm and wet Holocene (10,500 – 7,000 years ago)

The abundance of forest species (*Pinus, Quercus, Betula*) and aquatic taxa (*Botryococcus*, *Pediastrum*) during the early Holocene in Sierra Nevada indicates warmer and moister conditions than registered during the last 12,000 years. A very warm early Holocene could be explained by the maximum in summer insolation that was reached at this time and that caused a climatic warming. The maximum in moisture could be explained by greater contrast in temperatures between the land and the sea in the Mediterranean region during autumn, prompting heavier precipitation during autumn and winter.

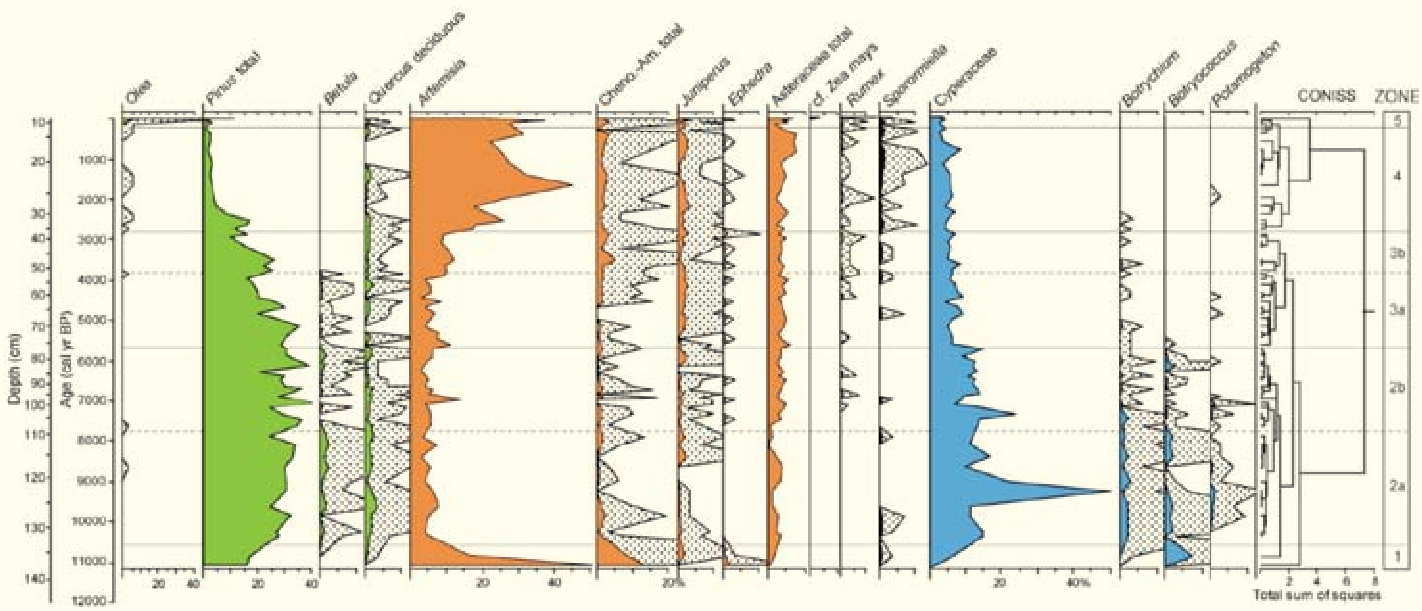
The cooling and aridification during the middle and late Holocene (7,000 ago– present)

The pollen record of Sierra Nevada shows a progressive process of deforestation and decline in aquatic species in the sedimentary record of the wetlands. This trend, which began about 7,000 years ago and intensified from 5,000 years ago onwards, could be accounted for by a progressive cooling of the climate and, above all, the growing aridity. This aridification has been deduced from other pollen records of the region (e.g. Sierra de Cazorla, Alborán Sea) and from many other palaeoclimatic indicators throughout the Mediterranean region (speleothems, lake levels, fluvial and wind input). This climatic change, falling temperatures, and advancing aridity, can be explained by the less intense summer insolation.

Climatic variations on the millennium scale

The trend towards aridity is characterized in the pollen record of Sierra Nevada by cyclic changes at a lower time scale. More severe droughts can be recognized around 6,500, 5,200 4,000-3,500, and 1,500 years ago. Some of these droughts are regionally and globally recognized (see abstract in [1]). One well-documented example is the drought that characterized the Medieval period, which was very clear in the pollen record

Figure 1



Synthetic diagram of pollen from Laguna de Río Seco. In green the tree species, red the grass species, blue the aquatic species. The right zones identified through time are indicated on the right side. Modified from [1].

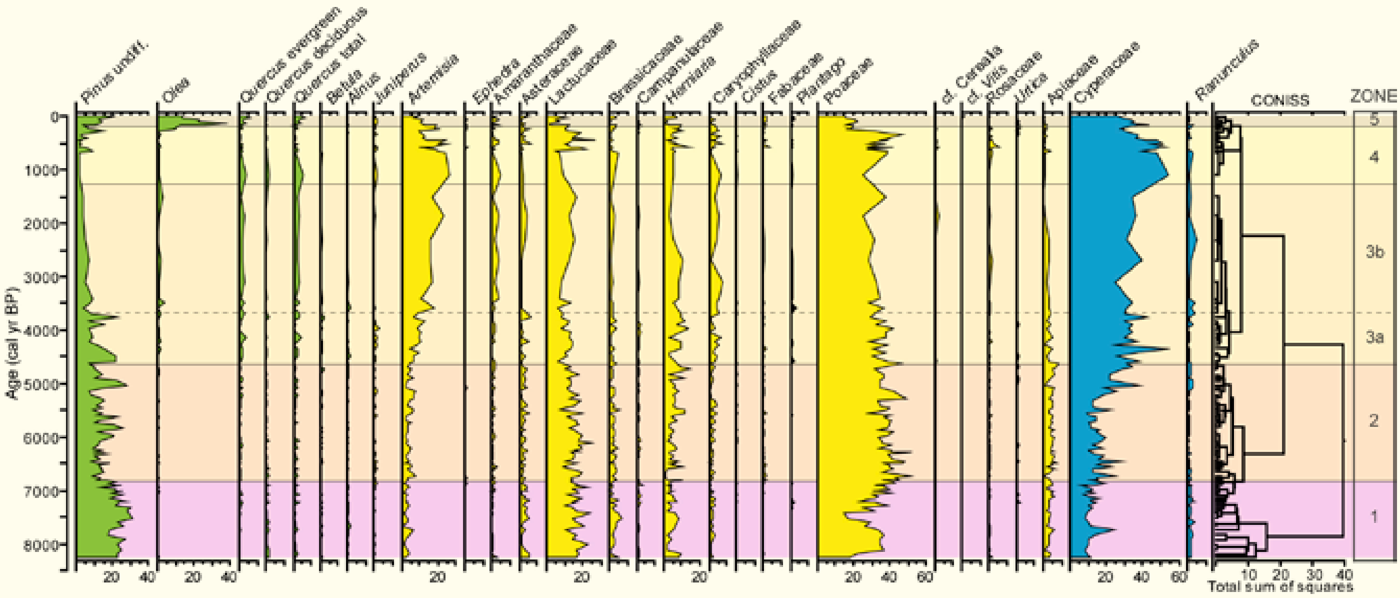
of Laguna de la Mula [3]. There were relatively moist periods between arid ones, as noted in Laguna de la Mula, coinciding with the moisture maximum of the Roman period [4].

These climatic variations are probably related to cyclic changes in the frequency of the North Atlantic Oscillation (NAO). Arid periods would be due to longer NAO + phases while wetter periods would be due to longer NAO - phases. These latter ones would give rise to heavier precipitation throughout the Mediterranean region.

Human impact on the vegetation: grazing and cultivation

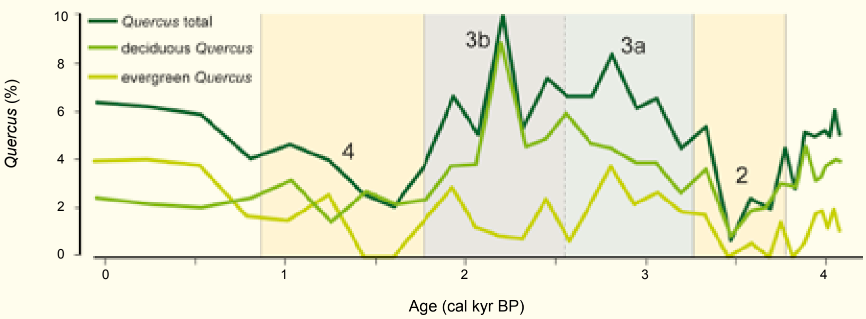
Multiple evidence indicate that from about 3,000 years ago to the present, human activity intensified in Sierra Nevada.From that moment onwards, fires frequency increased in this regions [3], together with grazing and mining activities. More recently, olive cultivation at large scale at the lowest elevations and reforestation activities have taken place.

Figure 2



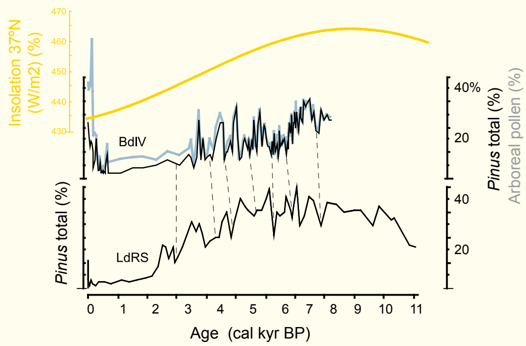
Synthetic diagram of pollen from Borreguiles de la Virgen. In green the forest species, yellow the grass species, and blue the aquatic species. Pollen areas identified over time are indicated on the right. Modified from [2].

Figure 3



Temporal evolution of the oak percentages (deciduous and evergreen) in the last 4,000 years recorded in Laguna de la Mula [3]. The maximum percentages of deciduous oaks were recorded during the wet Roman period (in blue). Two relatively arid periods are shown in yellow.

Figure 4



Comparison between the percentage of pines from Laguna de Río Seco and from Borreguiles de la Virgen [1-2], with the summer insolation curve at 37ºN. The trend corresponds to a deforestation (aridification) from 7,000 years ago onwards.

3.2. Analysis of the palaeolimnological indicators in the lakes of Sierra Nevada

Pérez-Martínez, C.
University of Granada

Río Seco lake

Abstract

The siliceous remains of diatoms and the fossil chlorophyll-*a* were analysed from the last 150 years in six lakes of Sierra Nevada. The chlorophyll-*a* values from all the lakes increased over the 20th century. The magnitude of the experimental variations in the diatom community over the last 150 years proved appreciably different between lakes, with Río Seco y Borreguil lakes showing the most notable differences.

The changes observed in the lakes appear to be related to effects (direct and indirect) of the higher temperatures recorded for this period. In addition to this regional response, local responses were found to be determined by the particularities of each lake.

Aims and methodology

The goal of this work is to study various paleolimnological indicators in several lakes of Sierra Nevada, especially useful to quantify the biomass production of these ecosystems. The temporal evolution of chlorophyll and its relationship with temperature are analysed. The morphological and limnological characteristics of the six lakes analysed are shown in Figure 1.

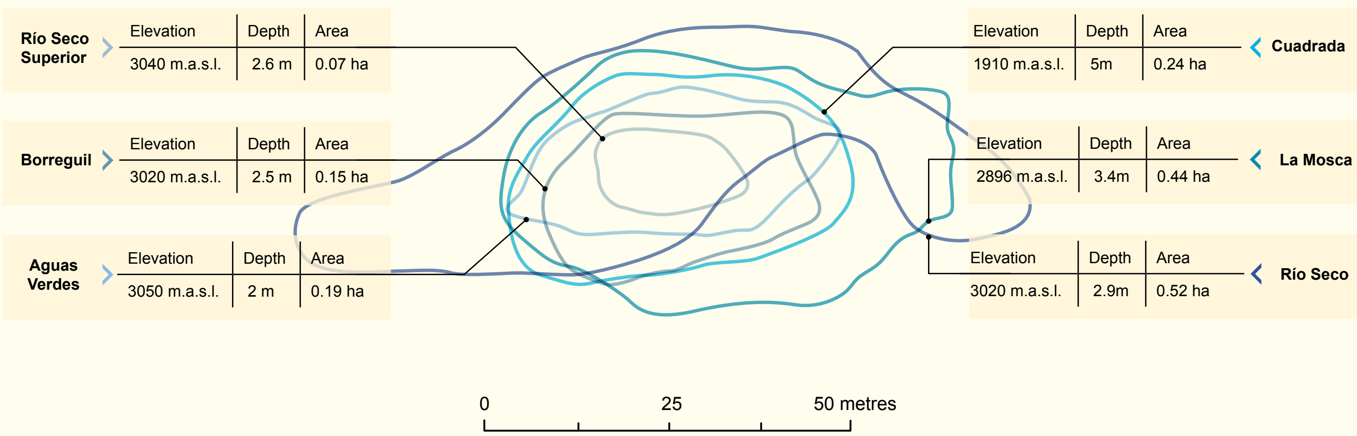
Siliceous remains of diatoms. The sediment samples were acid digested and the siliceous remains were mounted in slides with Naphrax for counting [6]. A minimum of 300 diatom frustules were identified and enumerated in each interval, using a light microscope at 1000x and differential interference contrast (DIC).

Chlorophyll-a analysis. The concentration of fossil chlorophyll-*a* (chlorophyll-*a* + derivatives) which were preserved in the sediments was inferred by the VRS technique (Visible Reflectance Spectroscopy) [7].

Gathering and treatment of climatic data. The temperature series was taken from station 3195 of Madrid (Retiro Park) since, despite being relatively far away, it offers one of the longest series available (since 1869) and has a good correlation with other shorter data series from the study zone, such as Armilla and Padul, and also with the climate series created by the Sierra Nevada Global Change Observatory. The precipitation series best correlating with the latter was that of the station of the San Fernando de Cádiz Military Base (since 1841).

Data analysis. A Principal Component Analysis (PCA) was performed with the relative abundance data of different diatom species. These data were correlated with the chlorophyll values in each lake.

Figure 1



Schematic representation of the lakes studied. The outline of the lakes and main features are represented.

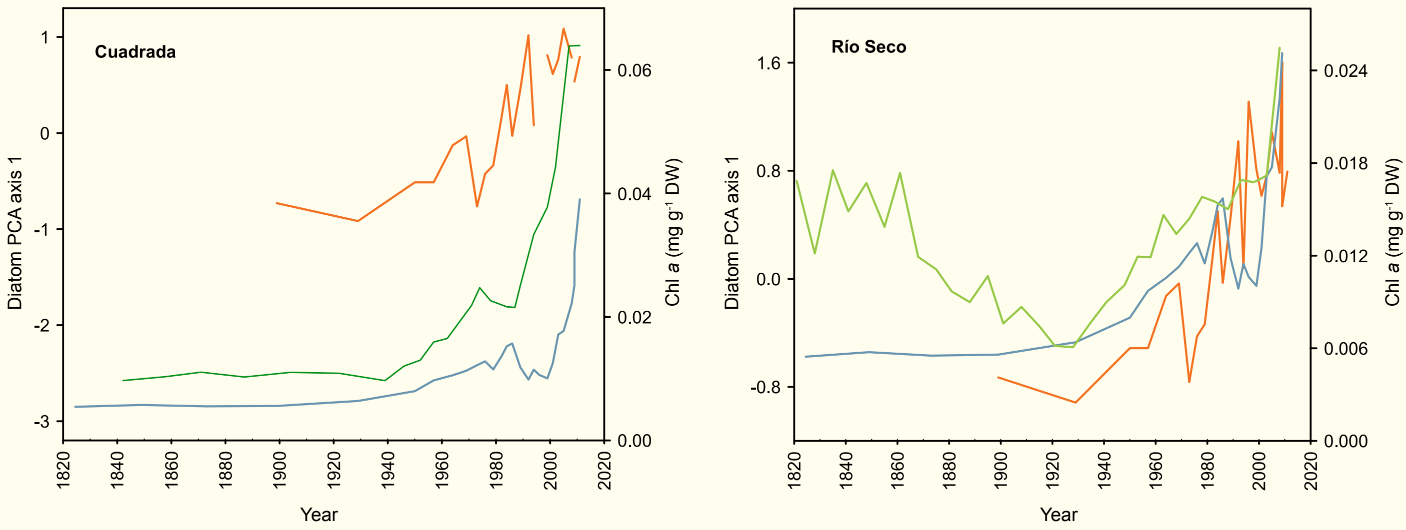
Results

The variations experienced by the diatom community over the last 150 years substantially differed between lakes. Río Seco and Borreguiles presented the most notable variations, followed by Aguas Verdes and Mosca, and finally Cuadrada and Río Seco Superior. Regarding the changes in the species composition it should be noted the increase in alkalophilous species and the decline in acidophilous ones as well as in epiphytes and tycoplanktonic species.

The values of chlorophyll-*a* in all the lakes show an increase over the 20th century, beginning in the first half of the century in Cuadrada and Río Seco Superior, and in the second half of the century in the other lakes (Figure 2).

The variable that summarizes the changes in the diatom community over time. Axis 1 factor scores of the principal component analysis (PCA) performed on the relative abundance of the diatom species is correlated with the chlorophyll values in each of the lakes (all $p<0.01$). With respect to the relation of these two variables to the available climate data, the six lakes rendered significant correlations between the chlorophyll-*a* values and the mean annual temperature values (all $p<0.01$), while the precipitation had a significant correlation only for Borreguil Lake. In addition, the changes undergone by the diatom community (PCA axis 1) showed a significant correlation with the mean temperature values for each of the lakes (all $p<0.001$) except in Río Seco Superior Lake, although the relation with precipitation was significant only for Río Seco Lake.

Figure 2



Changes in the composition of the diatom community (blue), time course of the values for chlorophyll-*a* (green) and for mean annual temperature (anomalies with respect to the period 1961-90, red) in Río Seco and Cuadrada lakes.

Discussion and conclusions

The increase in chlorophyll-*a* and the variations detected in the diatom community in the six lakes indicate that these systems have significantly changed in their limnological variables over the last 150 years. The robust relation of chlorophyll-*a* and the changes in the diatoms with temperature suggest a significant effect of rising temperatures on these aquatic ecosystems. The primary production of the system, represented by the chlorophyll-*a* values, responds to the direct rise in water temperature and furthermore to the indirect effects derived from the lengthening of the ice-free growing season [8]. Diatoms can reflect the climatic variability in different ways: direct effect of temperature, shift in thermal stability, or changes in water quality and habitat alterations [9]. Thus, the decline in tycoplanktonic species can be attributed to the greater thermal stability of the water column together with the diminished flow of water entering and leaving, as well as the mean depth of the lakes [10]. On the other hand, the increase in the pH derived from the temperature increase of the decline in acidophilous species and of the increase in alkalophilous species. Finally, the longer ice-free periods, higher temperatures and lower precipitation mainly since the 1980s account for the decrease in the water level of the lakes, as well as the lower degree of moisture in the alpine meadows. Under these conditions, the epiphytic diatom species could have less survival probability in these habitats. These factors would explain the differences in the magnitude of the response of the diatom community in the lakes in such a way that the lakes with the greatest surface area of surrounding meadows and the highest relation of meadows surface area to lake surface area (Río Seco and Borreguil lakes) presented more evident changes than those having a smaller meadows area and fewer changes in terms of water level (Aguas Verdes and Mosca lakes) and those lakes lakes without surrounding meadows (Cuadrada and Río Seco Superior lakes).

In short, the six lakes analysed showed significant changes in the diatom community and in the chlorophyll-*a* values during the last 150 years which appear to be related to the temperature increase recorded in this period. In addition to this response, which can be considered regional, local responses were found, determined by the particularities of each lake, such as the presence and size of the surrounding meadows, the morphometric characteristics of the lakes and their altitude.

3.3. Land-use changes in Sierra Nevada over the last 50 years

Jiménez-Olivencia, Y. [1]; Porcel-Rodríguez, L.[1]; Caballero-Calvo, A.[1] and Bonet, F.J.[2]

[1] University of Granada [2] Andalusian Institute for Earth System Research. University of Granada

Abstract

The different types of human intervention in nature through time have, in each historical period, helped to define a particular model of human-environment relations. Each of these models have decidedly influenced the landscapes of Sierra Nevada. The purpose of the present work is to monitor the great transformations that have taken place in land use and in landscape structure as a consequence of the profound changes that can be recognized in the socioeconomic context between the 1950s and ithe present. These changes have been notable in Sierra Nevada, where the forest surface area has expanded due to the abandonment of cultivation and subsequent recolonization of woody vegetation, due to reforestation and the densification of natural forest masses (oak forests).

Aims and Methodology

This study has three specific objectives:

- To quantify the magnitude of the land transformations from 1956 to 2006.
- To identify the main dynamics of social and economic transformation.
- To establish the way in which changes have taken place in the different types of landscape.

The method used to identify the changes in land use was a detailed interpretation of digital orthophotographs from the years 1956, 2006 and 2011. From this analysis, land-use maps have been constructed/built/drawn both at a scale of 1:15,000 for the entire Sierra Nevada as well as at a scale of 1:5,000 for specific plant formations.

This diachronic approach has enabled the analysis of the surface area occupied by each type of ground cover in each year, determining their variations as well as quantifying and locating the greatest transformations. All this has been approached using GIS tools.

With the purpose of determining the effect that land-use changes have exerted on the different landscape types, four broad categories were established, grouped according to the different units identified on the map of Sierra Nevada landscapes [1].

Figure 1

Map showing the land-use changes in Sierra Nevada (orange) from 1956 to 2006.

Results

The changes undergone by the landscapes in the half century under study affected some 42.8% of the protected area (Figure 1).

The maps of change dynamics for each type of ground cover indicate that (Figure 2):

- The surface area of tree formations has expanded from 15% to 51.23% of the total surface area of the Protected Area.
- Greater progression of the pine forests over the native forests. Oak species increased from 9.92% of the total surface area to 13.29% while conifers increased from 2.47% to 24.97%.

- Densification of the scattered tree cover and of the natural forests.
- Development of the riverbank formations in the main ravines of the sierra.
- Decline in the surface area occupied by cultivated fields, which occupied 17.8% of the total surface area of the Protected Area in 1956 and only 4.72% in 2006.
- Growth of constructed urban areas from 0.09% to 0.64%.

The transformations in the distribution of land uses have different effects on the different types of landscape:

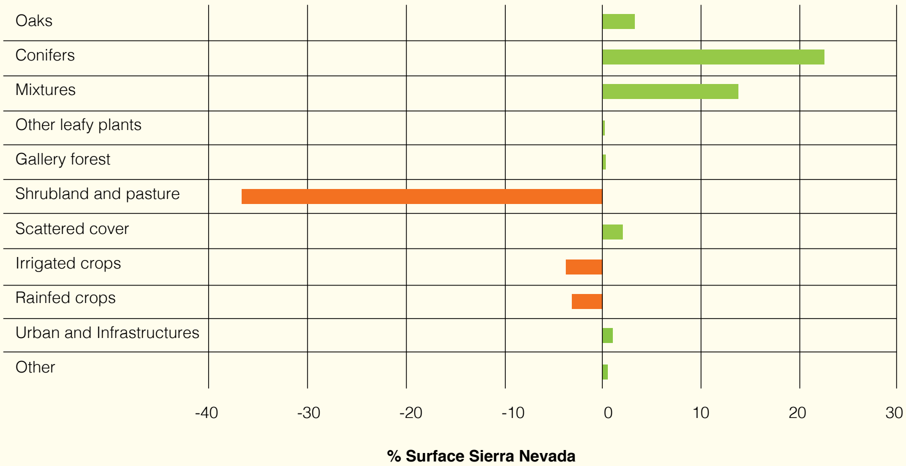
1. The natural landscapes of the high mountain (Alpine zone without trees):
    - Reforestation with conifers in potentially occupiable spaces by the juniper thickets and high-mountain pasture.
    - Abandonment of high crops or mountain crops and colonization of the fields by oromediterranean serial communities.
    - Construction of the ski station and subsequent extension of the urbanized area and the ski area.

2. The forest landscapes of the northern slope:
    - Replacement of mid- and high-mountain shrublands and pastures by broad extensions of very dense reforested pine.
    - Progression and consolidation of the native forest from the shrubland formations and pastures with scattered Holm oaks. Also, an elevational ascent was noted in the tree line.
    - Abandonment of rainfed farming followed by spontaneous plant recolonization.

3. The calcareous and agro-forest landscapes of the western valleys:
    - Broad stands of reforested pine that entirely surround the relict patches of *Pinus sylvestris* var. *nevadensis*. However, these relict patches are now denser and have a greater surface area.
    - Consolidation of some patches of oak woodlands at the heads of the rivers.
    - Colonization of the natural tree vegetation in abandoned agricultural areas.
    - Replacement of mixed crops by monospecific orchards of olives or almonds.
    - Urban occupation of the contact zone with the metropolitan areas of Granada (free spaces of the metropolitan area).

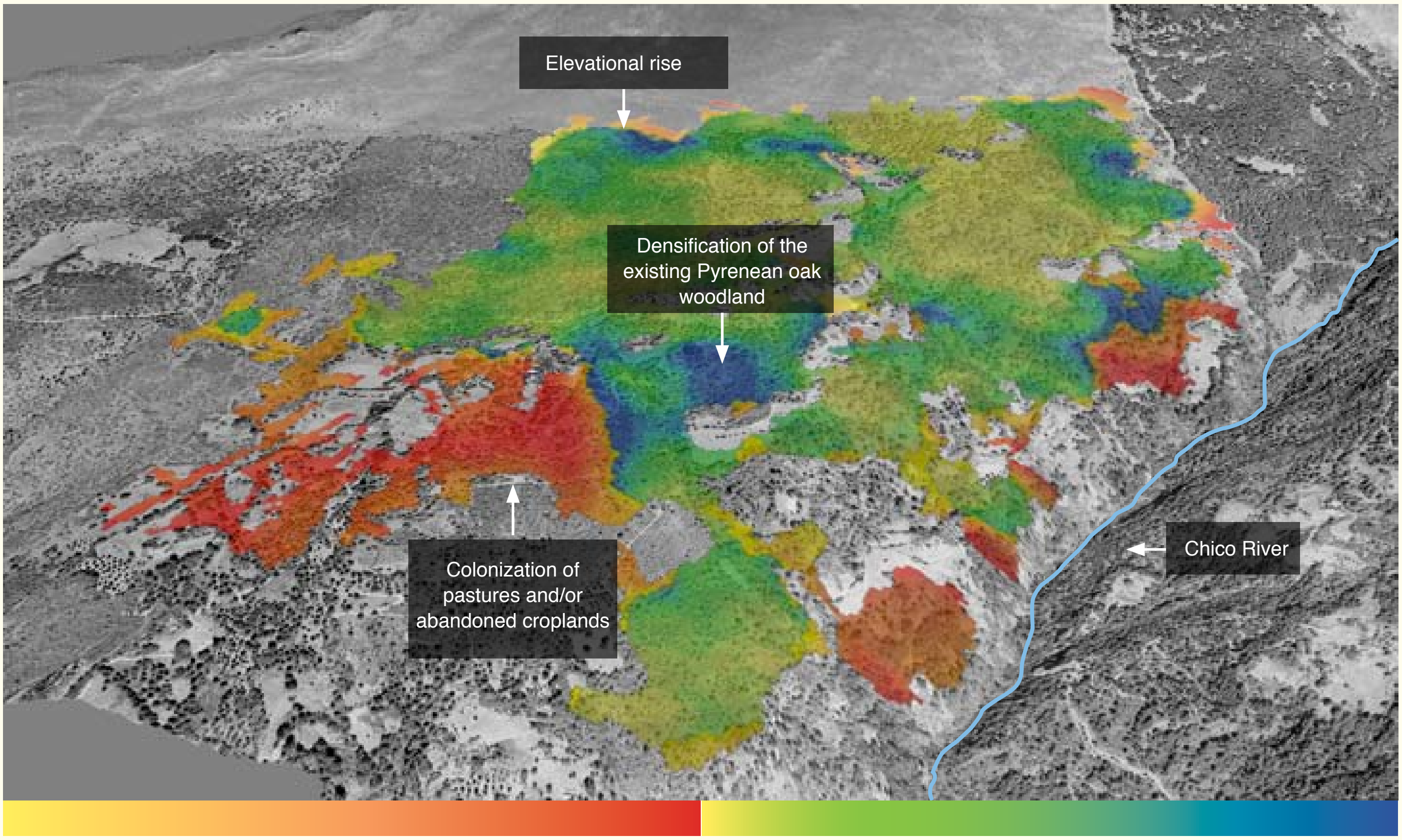
4. The agro-forest landscapes of the sunny slopes of the Sierra Nevada (Alpujarra and the southern slope):
    - Reforestation of the areas covered by shrublands and pasture with large extensions of conifers.
    - Increase in the surface area occupied by *Quercus ilex* and *Q. pyrenaica* woodlands. Also, the Pyrenean oak forest stratum has become denser and the tree line has shifted in elevation in some cases (Figure 3).
    - Abandonment of a large part of the agricultural area, which is colonized by natural vegetation.
    - Frequent replacement of traditional herbaceous and mixed crops by tree crops.
    - Growth of urban centres that affect the traditional urban structure and the profile seen from the exterior.

Figure 2



Changes in the percentage of occupation of the surface area of the main plant formation of Sierra Nevada. The great increase in the surface area of reforested pine and oak forests appears to be coupled with the reduction in the shrubland and pasture surface area.

Figure 3



Changes in density and extent of oak woodlands of Cáñar (southern face of Sierra Nevada). The yellow-blue colours show density changes at sites occupied both in 1956 and in 2006 by oak woodlands. A clear densification of the patches, was presumably spurred by the reduction in agricultural activities, can be observed. The yellow-red colours show changes in density in places where there were hardly any oaks in 1956 but where numbers rose in 2006. These were sites where oak woodlands extended their distribution. The slight ascent in elevation of the tree line is striking, as is the colonization of abandoned crops and pastures.

› Discussion and conclusions

The reforestation conducted in Sierra Nevada and the abandonment of the traditional agricultural area triggered the main changes in the study period. In addition, there was an increase in the areas transformed by the expansion of high-mountain recreational activities and rural tourism in the populations on the southern slopes of the sierra. The patterns of change observed at the scale of Sierra Nevada are strongly determined by human activity. This activity has altered both the functioning of natural ecosystems as well as their capacity to render ecosystem services, especially in the context of climatic change.

The interaction of both motors of change (land use and climate) results in a complex scenario that should be taken into consideration to design mechanisms of adaptation in the immediate future.

3.4. Historical analysis of socio-ecological changes in the municipality of Cáñar (Alpujarra, Sierra Nevada) over the last 5 centuries

Moreno-Llorca, R.A.; Pérez-Luque, A.J.; Bonet, F.J. and Zamora, R.
Andalusian Institute for Earth System Research. University of Granada

Abstract

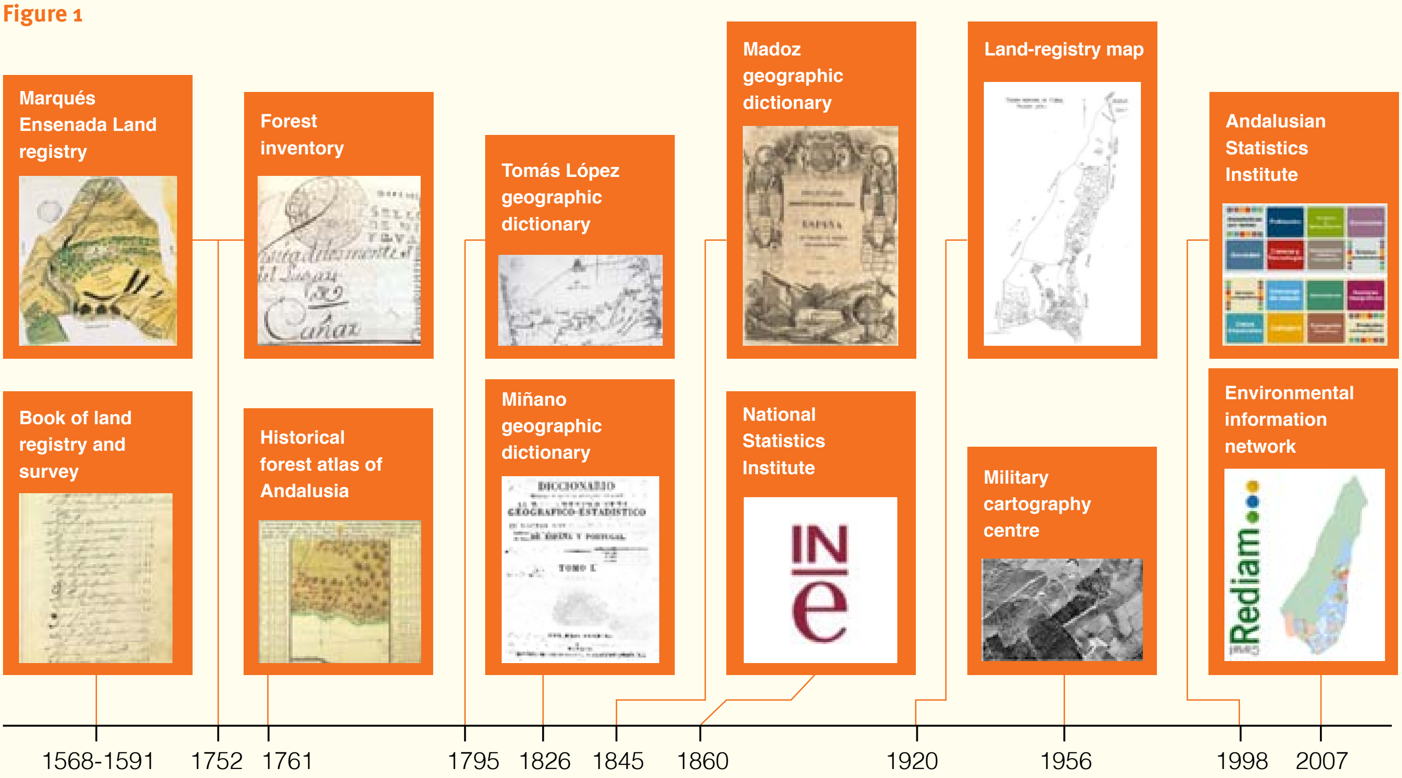
In order to understand the factors that have influenced the distribution and dynamics of current vegetation it is necessary to look into the past and to investigate the subsequent human management of the territory. In this sense, the gathering of historical information concerning both land use as well as the distribution of the vegetation constitutes a prime element for comprehending the implications of global change in Mediterranean contexts.

Aims and methodology

A detailed historical analysis was made on the use changes of the territory in the town of Cáñar (Alpujarra, Granada). Documentary sources were reviewed from 1568 to the present (Figure 1) to compile information concerning the distribution of vegetation and crops, land uses, and other variables that could be related.

A series of variables were selected to describe the changes that occurred in the socio-economic dynamics of the town and their ecological consequences:

Figure 1



Set of documentary sources used in the work.

population, land use (surface area of irrigated crop, rainfed crop, and forest surface area), tree density, sheep raising, beekeeping, and economic sectors (primary, secondary, and tertiary). All the variables were gathered at the municipal scale, except for those related to the economic sectors, which were established at provincial level. The temporal range of each variable differed according to the data availability. After the collection of data, the changes that occurred in the land use and the dynamics of the vegetation were inferred from a multidisciplinar approach (Figure 2).

› Results

The compilation enabled the reconstruction of the time course of a number of socioeconomic variables intimately related to the changes detected in the structure of the landscape and vegetation. These relations still persist. Their description and analysis will help improve the way in which the natural resources are managed in a context of global change. From the reforestation undertaken by the Catholic Monarchs in 1571 after the expulsion of the Moors, a sustained reforestation was pursued, reaching a maximum at the end of the 19th century. From this time on, the number of inhabitants were maintained with certain fluctuations until the 1960s. Since then, coinciding with the crisis of the Spanish mountain [16], the population of Cáñar and the rest of the Alpujarra began a sharp descent.

The date of the onset of the demographic decline coincides with the pronounced drop in livestock and beekeeping. This trend has continued to the present. The abandoned fields have been colonized by natural formations of vegetation, with an expansion in the forest surface area from the middle of the 20th century to the present.

The above trends are reflected also in economic indicators by sectors: The primary sector was drastically reduced. While the rest of the province underwent this retraction in terms of the secondary and tertiary sectors, in the case of Cáñar and the Alta Alpujarra it was more related to emigration away from Granada (to northern Spain and abroad).

› Discussion and conclusions

The changes in the human population have left a footprint in Sierra Nevada. These changes have provoked successive alterations in the patterns of natural resources use as well as land use. The first available data about population correspond to the period of the Moorish rebellion and the subsequent war (1568-1571). At this stage, both sides practiced the strategy of the “burnt land”, i.e. destroying infrastructures, thereby seriously affecting the complex irrigation-channel network [17]. This fact, added to the lack of knowledge concerning the irrigation by the settlers that arrived with their cereal and livestock practices triggered a major abandonment of irrigation. In 1571, after the expulsion of the Moors, agriculture became extensively herbaceous with the ploughing of broad forested areas for this type of farming [18]. This rainfed agriculture lasted until the end of the 18th century, when a change occurred in the agricultural model. Irrigation returned as a central element, replacing cereal cultivation and vineyards. This period significantly boosted agricultural output.

The farming activity expanded from the end of the 18th century to the end of the 19th century, when Cáñar exported silk and products made in the liquor factory as well as in four flour mills [19]. In this period, Cáñar reached its largest population (1063 inhabitants). Then, with the arrival of phylloxera (the pest that attacked grapevine roots) and the cholera epidemic (1885), the population shrank, with heavy emigration to Argentina and Brazil.

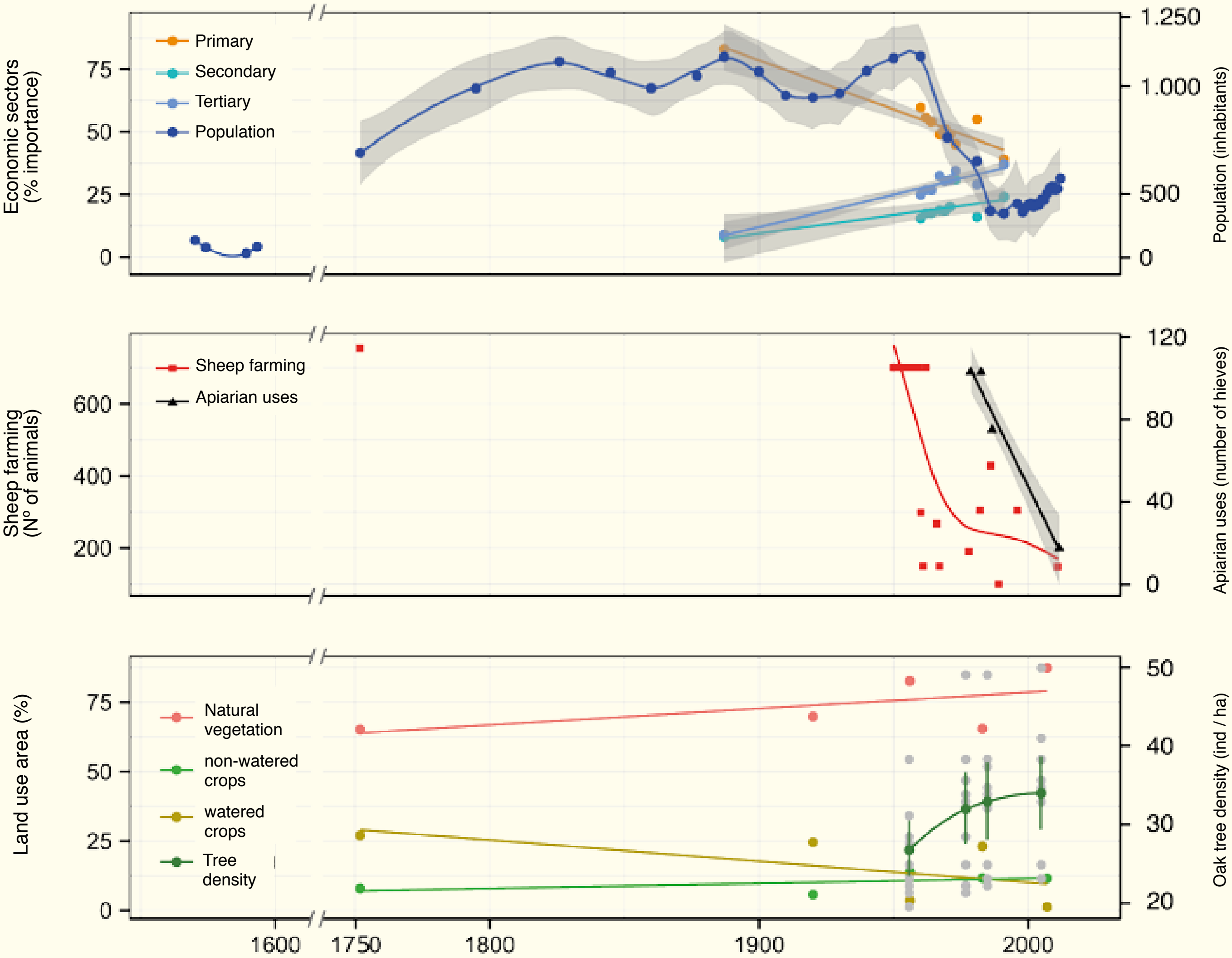
The strong human pressure, which translated as the ploughing of forest areas, the exploitation of wood, and the forest fires provoked the disappearance of 90% of the surface area occupied by oak woodlands on the medium and low slopes [12]. The last massive felling of trees occurred in 1930.

The ploughing of forest areas unleashed erosion and continuous flooding, prompting the local administrations and those affected to call for action to palliate the continuous catastrophes in the Guadalfeo river from 1860 on [12]. The first reforestation efforts began in 1929 in the rivers Sucio (Lanjarón) and Chico (Cáñar and Soportújar), mainly with *Pinus pinaster* and *Pinus uncinata*. At present, the reforested pines stand as a major element in the landscape.

The war and post-war periods in Spain left a depressed local population until the end of the 1960s, given the difficulty of emigrating and the possibility of maintaining a life of subsistence based on livestock and farming [20]. After this time, a strong emigration started, resulting in massive abandonment of the two means of subsistence. Between the end of the 1950s until the 1970s, the highest and least accessible areas were abandoned. From 1974 on, the lowest slopes began to be left behind. This abandonment became moderate in the 1980s, leaving mosaics of cultivated plots.

This situation allowed the oak woodlands to regenerate in the abandoned fields. Therefore, there are two historical momments when herbaceous crops become new formations: at the end of the 18th century at the lowest elevations, where they were replaced artificially by woody crops (mainly vineyards); and from 1957 on, with a generalized abandonment of livestock and farming and the beginning of the recolonization of abandoned fields by the native vegetation.

Figure 2



Temporal evolution of the variables studied from 1568 to the present.

Figure 2 displays the coincidence in time of the increase in the forest surface area and of its density with the decline in livestock and farming. Other similar uses such as beekeeping also reflect the abandonment of the primary sector.

In the last two decades, coinciding with the declaration of Sierra Nevada as Natural Park, the population of Cáñar began a slight recovery. In this period, in the Poqueira Valley (largely due to the surge in tourism) and in the river Chico area, a certain irrigated orchard activity has revived [18].

The results found contribute not only to a better understanding of the history of the territory but also to the recognition of the situation of the system facing the impact of global change. Diverse key ecological functions for the generation of ecosystem services (biomass production, land creation, etc.) are determined by the land use in the past.

Crops in the way up to "Robledal de Cáñar" in the 1970s

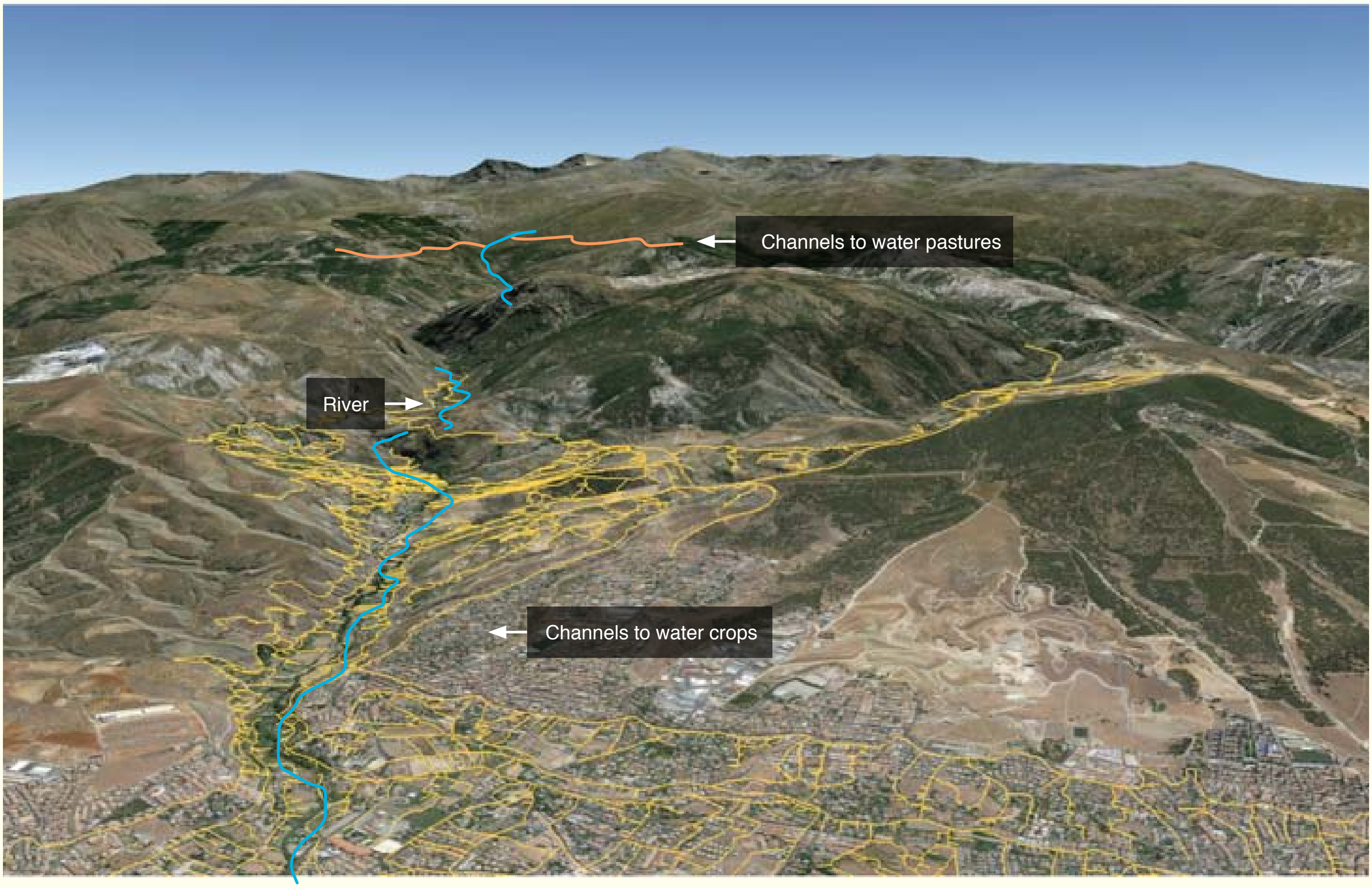
3.5. Historical irrigation systems and cultural landscapes of Sierra Nevada

Martín Civantos, J.M. and Bonet-García, M.T.
University of Granada

Abstract

The historical systems of irrigation and water management are among the main badges of identity of Sierra Nevada. Their construction in the Medieval period has left an indelible mark not only on lifestyles of the inhabitants and their exploitation of resources, but also the profound human transformation of the mountain landscape [21,25]. These networks of irrigation channels are fundamental not only for high-mountain aquifer recharge, the creation of pastures, and the opening of areas for intensive irrigated agriculture, but also for the maintenance of the biodiversity of this mountain area through a broad number of ecosystem services that until now have hardly been considered within the scientific ambit. However, despite the enormous territorial impact, the thousands of kilometres of irrigation channels, the crop terraces, and the infrastructures associated with them are today jeopardized by the lack of profitability in the current economic framework. The progressive disappearance of traditional exploitation and the gradual drop in farming income has been accompanied by marginalization, deterioration, and partial abandonment of these systems.

Figure 1



Graphic representation of the structure of a typical irrigation channels network of Sierra Nevada. These channels are structures designed to carry a certain percentage of the flow from a natural water course (in blue). In the high course of a river, this water is used to irrigate slopes and foment both the infiltration of water into the aquifers as well as the growth of mountain pasture. These are called *acequias de careo* (orange). In the lower areas, the water from the acequias was used to irrigate extensive farms typical of the Mediterranean (orchards, in yellow).

Aims and methodology

From 2010 to 2014, the mountain irrigation systems of Sierra Nevada were studied under the funding of the National Park Service. The study methodology was intricate, including not only water prospection [21, 22] for the documenting and mapping of the network of irrigation channels but also the ethnological interviewing of irrigators and persons with irrigation experience in traditional farming.

The mapping was undertaken by GPS in the field, in addition to the use of orthophotographs, as well as, wherever possible, historical cartography. This documentation was stored in a geographic data base and implemented on an informatics platform, creating a geographic information system. The work included a documentary and bibliographic search, a toponymic analysis, and even the excavation of several farming terraces to study the soil dynamics and formation of terracing systems for cultivation.

Results

The most striking result of the work performed is the documentation and mapping of somewhat more than 2000 km of acequias in Sierra Nevada and its immediate area. These are, however, a small part of those that still exist and that need to be studied. In order to have an idea of the number of irrigation channels in Sierra Nevada and the municipalities therein, some estimations can be made according to the data compiled. During this study, only in the town of Ferreira, 423 irrigation channels were documented, constituting 117 linear km of channels, including the cultivated land and open terrain (occasionally irrigated), throughout the municipality, which occupies a surface area of 43.5 km^2. If these figures are extrapolated to the municipalities of the district Marquesado del Zenete (with the villages Aldeire, Alquife, Dólar, Huéneja, Jérez del Marquesado, Lanteira, and La Calahorra), which add up to 452 km^2, the total is 1215 km of irrigation channels. Another example for the southern slope of Sierra Nevada would be the irrigation systems supplying the municipalities of Monachil, La Zubia, Huétor Vega, and Cájar, which occupy a surface area of , 114.7 km^2, where 300 km of irrigation channels were recorded (Figure 1 shows a scheme with the distribution of these irrigation channels). If, again, these figures are extrapolated to the municipalities on the southern face of Sierra Nevada (Bubión, Busquístar, Cáñar, Capileira, Soportújar, Pampaneira, Pórtugos, La Tahá, and Trevélez), which occupy some 285 km^2, the total would be some 745 km of irrigation channels. Another fact to consider when analysing irrigation systems and their current development is that

Traditional irrigation channel in Sierra Nevada out of more than 3,700 digitalized channels in this study, roughly 640 are abandoned or have disappeared. That is, there are an estimated 2,000 km of acequias in Sierra Nevada. The percentage of abandoned acequias is around 15-20% of the total.

Just the extent of the network gives an idea of the landscape, environmental and territorial impact of these structures and of the agrosystems linked to them. This is a complex management system not only of water, but also of soil, pasture, mountain vegetation, and of course of crop and animal husbandry. The diversion of part of the natural flow of the rivers into the irrigation channels system could alter aquatic ecosystems as well as terrestrial ones (irrigated by the water from irrigation channels). The mapping of the irrigation channels network provides valuable information for quantifying the effect of this network in the water cycle (through its inclusion in hydrological models, for example). Knowledge of the distribution of the irrigation channels will also enable the design of future works to evaluate the ecological effect of this irrigation system.

The main agricultural activity in Sierra Nevada has traditionally been intensive irrigated agriculture. This is a social option, perhaps not the most suitable one in a mountain and high-mountain setting. This option has its historical roots in the Arab-Berber conquest of the area in the 8th century, when the network of irrigation channels of Sierra Nevada began to be extended [23]. These networks included the artificial recharge of the shallow high-mountain aquifer and recharge of the depths, as well as the creation of the farmland at the lower elevations. Detailed knowledge of the distribution of the irrigation channels would enable a deeper understanding of these hydrological aspects that have great relevance at the local as well as landscape scale.
The area of influence of the Sierra Nevada Protected Area is far greater if the services that it provides hydrological systems are taken into account, these including the high-mountain aquifer recharge and the flooding of flat surrounding areas, as well as the agricultural supply in the faraway areas of the surrounding plains in Guadix, Granada, Delta del Guadalfeo or Almería. The study performed identified the hydrological connections between the mountain and the low, adjacent agricultural areas.

Thus, one important part of the history of Sierra Nevada and its populations can be traced through these systems of exploitation.

Discussion and conclusions

Communities that use irrigation have historically been responsible for thewater management as well as of these productive areas, carrying out crucial tasks from the standpoint of production, environment, and society [24]. Currently, these are in a process of ageing and crisis because of the lack of generational turnover and due to changes in life styles in the rural environment. The current economic framework and the protracted crisis of agricultural profitability make this type of farming uncompetitive in terms of the market, and it does not attract young farmers that could live from primary activities.

The knowledge associated with the management of the water systems as well as the crops and livestock in the mountain is in an accelerated process of disappearance, and is necessary to preserve it as much as possible.

From the Sierra Nevada Protected Area itself, awareness has risen in recent years concerning the importance of human management of the resources and of its role in maintaining biodiversity and landscapes. The project developed for the recovery of a good number of irrigation channels in the high areas of Sierra Nevada is a clear example of this. However, the problems related to the crisis in traditional agriculture are highly complex to manage. The lack of competitiveness in a globalized market can be offset only by a shift to environmental and social quality, with changes in the management models and marketing. For this, some general actions can be proposed:

- To continue studying these systems to improve and plan their management, as well to publicize their values.
- To formulate a plan to promote sustainable agricultural activity from the environmental and social perspectives, in order to encourage the traditional uses of resources, especially water, through the irrigation channels and aquifer recharge, the generation of high-mountain pasture and crop areas together with zones of intense irrigation.
- To encourage dialogue between the authorities of the Protected Area and the rural communities, especially the communities using irrigation for conservation and for social uses of the territory.
- To prepare a dissemination plan of the values of the irrigation systems to the general citizen as one of the most distinctive elements of the Protected Area and an example of the way to maintain the historical relation of the human with the natural surroundings in the context of global change.
- To act in defence of the rights of water use among the irrigating communities within the context of the European Directive of Waters and the Andalusian Water Laws, seeking a balance that will guarantee the continuity in traditional uses of water and the landscapes historically generated by them.

3.6. The importance of past land uses in the natural regeneration of Holm oak woodlands under pine plantations

Pérez-Luque, A.J.; Navarro, I.; Bonet, F.J. and Zamora, R.
Andalusian Institute for Earth System Research. University of Granada

Abstract

The natural regeneration under forest plantations depends on the degradation degree of the site, the proximity to seed sources, the availability of dispersers, and the intrinsic characteristics of the reforested patches (density, elevation, radiation, etc.). However, to date, no work has explicitly analysed the simultaneous influence of land use in the past and of the ecological factors in the regeneration of the native woodlands in reforestation stands. This is of paramount importance in Mediterranean ecosystems that have been submitted to a long history of human intervention, as in Sierra Nevada. In this work, the natural regeneration of oaks in reforested conifers is analysed as a function of land use in the past and of ecological factors. The results indicate that the soil use in the past is more important for the natural regeneration than the distance from the seed source or the plantation density. In fact, there is a gradient of natural regeneration according to the gradient of intensity of use in the past: the higher the use intensity in the past (crops), the lower the natural generation will be in the present, and *vice versa*. These results hightlight the need to consider past land use when evaluating the potential of recovering native vegetation in pine plantations.

› Aims and methodology

The starting hypothesis of this study is that the regeneration of the natural forest in reforested patches depends largely on the past use (legacy) prior to the establishment of the plantations. In this sense, the aim is to understand the importance of land use and the ecological factors in natural regeneration. For this purpose, the quantity of natural regeneration (*Quercus ilex*) in reforested pine stands was analysed as a function of land use in 1956 and of the ecological factors: the density of the reforested part and the distance to the seed source [26, 29]. A total of 168 plots were selected from the forest inventory of Sierra Nevada (Sinfonevada, [27]), which presented a pine cover greater than 75%, located below 1900 m.a.s.l. (physiological limit for oaks). By photointerpretation, each plot was assigned its land use for 1956. Four levels were established (gradient of use intensity): oak woodlands, shrublands, pastures, and crops. The distance to the seed source was calculated as the mean distance from each plot to the seed source in 1956 and at present. Individual and combined models were built to determine the contribution of each factor (land uses in 1956; density of the plantation and distance to the seed source) to natural regeneration.

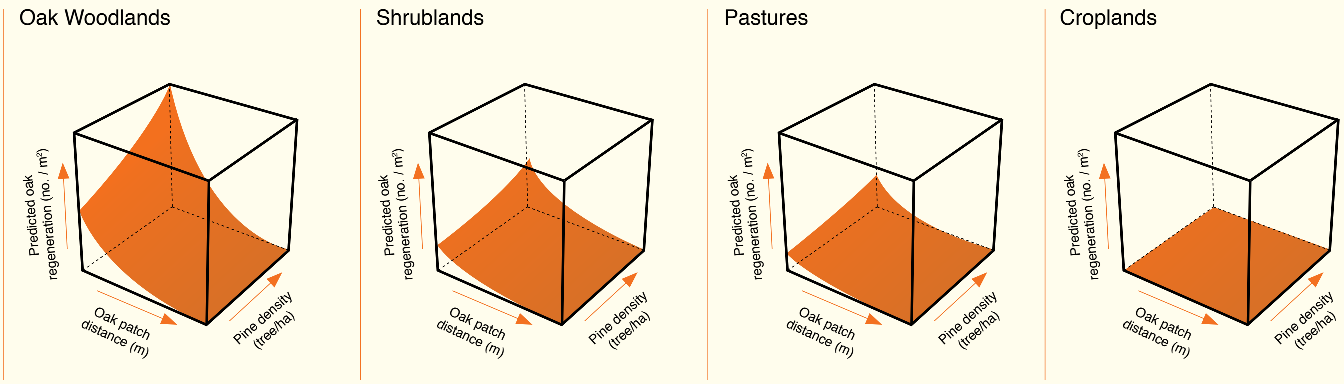
› Results

The model that best explains the natural regeneration is the one that includes all the factors analysed (complete model): land uses in 1956, distance to the seed source, and pine density. The analysis of the individual models showed that the type of use in 1956 was the factor that best explained the natural regeneration under the reforested pines [29, 30].

The probability of finding regeneration was greater in the plots that had oaks in 1956 than in the plots with other types of use (shrubland, pasture, crops). On the other hand, the density of the reforested areas (number of plants per square meter) was strongly influenced by the type of land use in 1956. At the optimal pine density (see [26]) and at zero distance from the seed source, the expected regeneration values were 0.01 seedlings/m^2 for plots that were cultivated in 1956, 0.11 seedlings/m^2 for pastures, 0.17 seedlings/m^2 for shrublands, and 0.38 seedlings/m^2 for Holm oak woodlands (Figure 1).

The distance to the seed source significantly affected both the probability of natural regeneration under under the pine cover as well as the abundance of the regenerated parts. The expected regeneration values decreased exponentially with the distance from the seed source (Figure 1). On the other hand, the density of the pines significantly influenced the natural regeneration found (Figure 1).

Figure 1



Natural regeneration of oaks under reforested pines according to the type of land use in the past (landuse in 1956: oak woodlands, shrublands, pastures and crops), the distance to seed source and the density of the reforested area.

Discussion and conclusions

Several ecological factors have been identified to affect natural regeneration under reforested conifers [26, 28], such as proximity to the seed source and the internal characteristics of the plantation (density, elevation, radiation, spatial heterogeneity). However, no work to date has shown the importance of past land use in natural regeneration. Our results indicate that the natural regeneration of reforested areas depends more on the type of land use in the past than on ecological factors. Furthermore, the present work demonstrates a regeneration gradient that coincides with the gradient of use intensity—or, stated in another way, the intensity of use in the past affects natural regeneration in the present.

These results indicate that the weight of the past (land use) largely determines the natural regeneration under reforested pines, apart from other ecological factors such as abiotic conditions, the structure of the landscape, and the composition of the vegetation [26, 28]. In this sense, management actions in conifer reforestation should consider not only the current ecological factors of the plantations but also the uses prior to the reforestation.

Natural regeneration of Pyrenean oak (*Quercus pyrenaica*) under pine plantations

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› More references at http://refbase.iecolab.es/ref_dossier_resultados.html

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Chapter 4

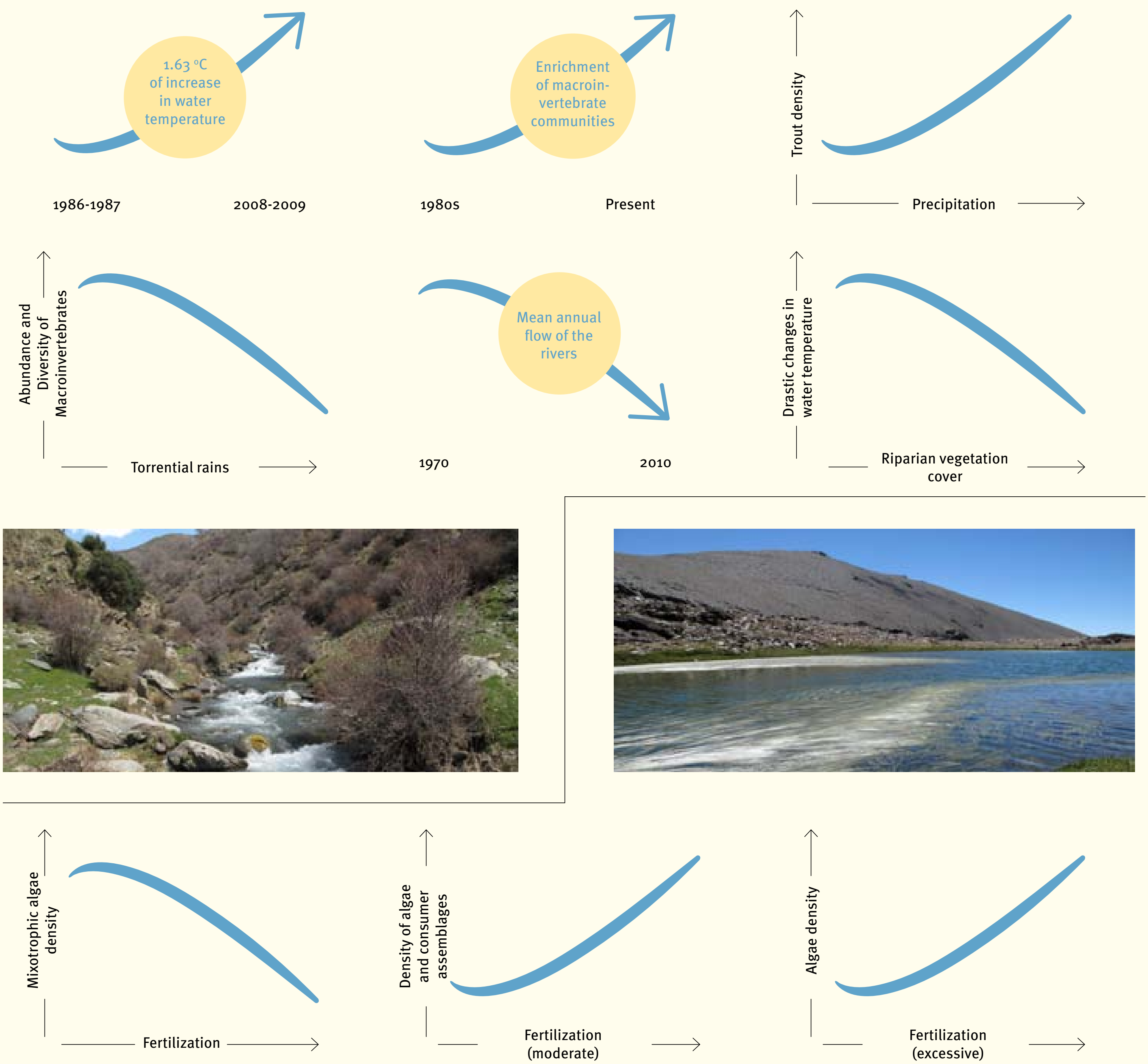
Aguas Verdes lake (3030 m.a.s.l.), the water of which gives rise to Veleta river.

Global change impacts on rivers and alpine lakes

The aquatic systems of Sierra Nevada are extremely sensitive to environmental changes. The comparison of water temperatures of the rivers (closely correlated to air temperature) in two separate periods 20 years apart (1984-1987 and 2008-2009) in a group of representative sites shows a rise of 1.63 ºC. This progressive heating of aquatic systems is also exacerbated by a gradual deterioration in the riverside vegetation, which provides these riparian environments a barrier that buffers against thermal oscillations. These changes have repercussions of extreme importance for the physico-chemical processes and the biological communities of the rivers. The comparative study of the macroinvertebrate communities of Sierra Nevada in the 1980s and at present highlights substantial changes. Certain species that in the 1980s were associated with the middle reaches have moved to higher elevations. As a result, the species diversity in the high mountain is now higher than 30 years ago. At sites where water temperatures have changed the most, there have also been larger increases in the diversity of Tricoptera. In the particular case of Plecoptera, the lower distribution limits of certain species have contracted, while no such changes were found at the upper limits.

Common trout is also affected by global change in mountain rivers. Sierra Nevada harbours the most abundant common trout populations in all of Andalusia. The monitoring undertaken during the last 9 years has established a clear relation between the flow volume of the rivers and trout abundance. Nevertheless, it has been observed that the population response of the trout to the variations in rivers flow is not immediate. That is, in a year of drought, the trout population diminishes for the following two years, while the reverse process occurs after a rainy year. Similarly, the data collected have documented the harmful effect of torrential rains, which depress the trout populations. In any case, the populations recover immediately after the floods.

The summits of Sierra Nevada have scattered lakes of glacial origin. In total, there are 74 lakes of different sizes that behave as sentinels of global change. This is demonstrated by more than 40 years of study of glacial lakes in Sierra



Graphical summary of the main results described in this chapter. Temporal trends of biophysical variables and relationships among variables are shown.

Nevada evidencing that these ecosystems are extremely sensitive to climate anomalies, to increased UV radiation, and to the deposition of atmospheric dust from the Sahara Desert. The present chapter explains some of the long-term studies carried out at Lake Caldera, which enable links to be established between global change and the loss of taxonomical and functional diversity of the high-mountain lakes of Sierra Nevada. For instance, mixotrophic algae (i.e. those with autotrophic and heterotrophic metabolism) are seriously affected by global change, causing the collapse of the heterotrophic microbial network. The fertilization that takes place in the form of inputs of phosphorus and other nutrients from the dust depositions from the Sahara Desert, also affects the trophic chain, reducing the quantity of herbivorous zooplankton.

4.1. Monitoring water quality in the rivers of Sierra Nevada

Fajardo-Merlo M.C.[1]; Sáinz-Bariáin, M.[2] and Zamora-Muñoz, C.[2]
[1] Environment and Water Agency of Andalusia [2] University of Granada

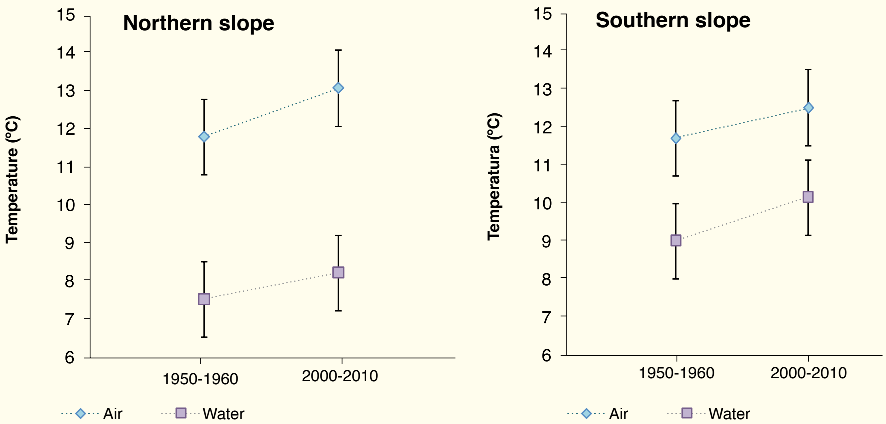
Abstract

Aquatic ecosystems are completely dependent on the environmental conditions surrounding them and global change alters the heat and water cycles, endangering the delicate equilibrium of these systems and of the organisms that inhabit them. Therefore, a retrospective analysis has been made of the environmental changes that are expected to have the strongest repercussions on aquatic environments, in order to suggest new measures for their future conservation.

Aims and methodology

For the ecological and chemical monitoring of rivers, several physico-chemical parameters (pH, electrical conductivity, dissolved oxygen, and temperature) have been locally measured in each of the sampling seasons (spring, summer, and autumn) at 23 sites distributed in 8 rivers. In addition, data loggers for continuous temperature records were located in 10 sampling sites in 2009, measuring data until 2014. Similarly, in 2009 water temperature data loggers were installed in 4 high-mountain lakes (La Caldera, Laguna Larga, Río Seco, and Aguas Verdes), and variations in the water level were measured using hydrostatic pressure in three of them (La Caldera, Laguna Larga, and Río Seco). Water flow was locally measured during samplings and, in addition, data published by the Centre for Hydrographic Studies of CEDEX of the Environment Ministry (http://hercules.cedex.es/ general/default.htm) on the gauging station belonging to the Guadalquivir Hydrographic Confederation (Confederacion Hidrografica del Guadalquivir) were used. Air-temperature data were provided by the Environmental Information Network of Andalusia.

Figure 1



Air and water temperature (mean and 95% confidence intervals) of the Alhorí (northern slope) (left) and Trevelez rivers (southern slope) (right).

Results

The comparison of the mean air temperature over two rivers situated on both slopes of the Sierra Nevada between the two decades 50 years apart (1950-1960, 2000-2010) revealed a rise of 1.5ºC (Figure 1), which must have had a strong repercussion on the mean temperature of the water of the rivers and streams.

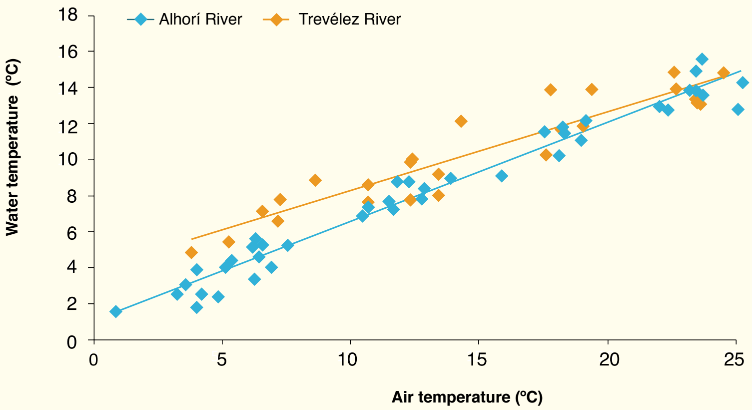
The air temperature was positive and significantly correlated with that of the water at these two sampling sites (Figure 2). It was estimated an increase of 0.5 ºC of the mean water temperature between aforementioned decades and the current one. In addition, the water temperature was compared in two study periods 20 years apart (1984-1987, 2008-2009) at 19 sites all over the Sierra Nevada, indicating a mean temperature increase of 1.63 ºC (Figure 3). The stronger effect was detected on the rivers situated on the southern slope.

An important factor to take into account with respect to the thermal oscillations of the water over the day is the presence of riparian vegetation [1], as seen when comparing two sites of the Andarax river with and without riparian vegetation due to elevation. The thermal fluctuations were softened up to 4 ºC in the summer season in the site with riparian vegetation (the lowest in altitude).

Analyses of the flow data (annual averages) have shown a slightly decrease trend in three of the four studied rivers (Alhori, Dilar, Genil, and Monachil) in recent years (Figure 4).

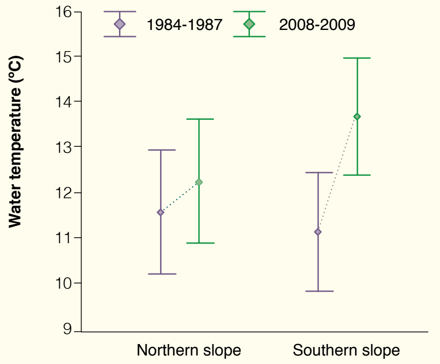
In the case of the high-mountain lakes, for Laguna Larga, a thermal inversion was detected during the winter period, when the surface of the lake was ice covered. Thermal inversion dissapeared in spring due to heating of lake surface. Thawing water provoked an abruptly descence of water column temperature. In summer, the sunlight increased the temperature of the water surface, being somewhat colder deeper without reaching a situation of marked thermal stratification, as it forms a layer more or less homogeneous by wind influence on the surface [2].

Figure 2



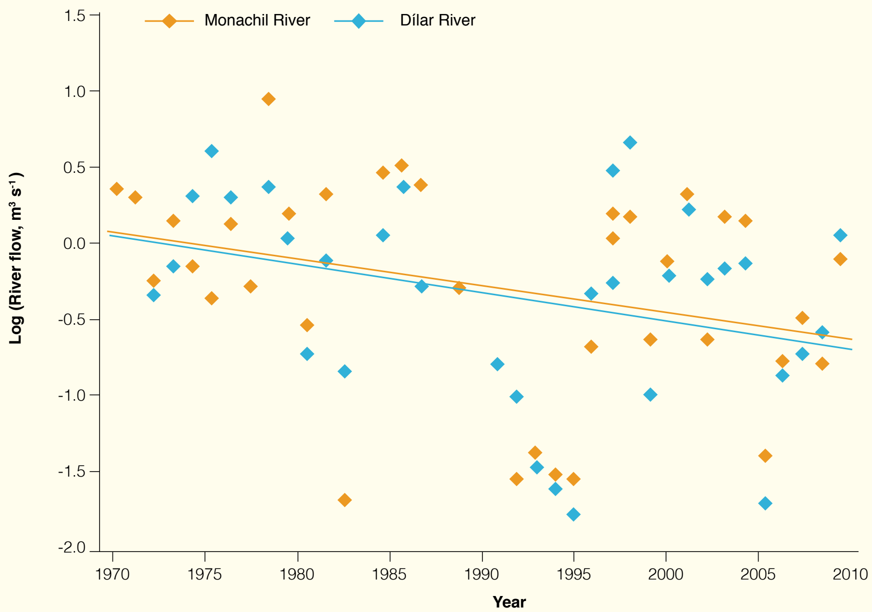
Linear regression between mean monthly air and water temperatures for the rivers Alhorí (northern slope) and Trevélez (southern slope) (Alhorí R^2= 0.966, Trevélez R^2= 0.898).

Figure 3



Mean water temperature (± 95% CI) at the northern and southern slope of the Sierra Nevada streams and rivers in the two studied periods, 1984–1987 and 2008–2009.

Figure 4



Trends in mean annual flow (in logarithms) for Dílar and Monachil Rivers in recent years.

Discussion and conclusions

The future of aquatic ecosystems from the Sierra Nevada is uncertain due to the potential effects of global change. On the one hand, the riparian vegetation has diminished due to human activity. On the other, air temperature, directly related to water temperature, has increased; being stronger the effect with a low river flow [3]. Also, the gradual decline in river flow in recent decades is giving rise to changes in the thermal regime of the rivers and streams of the Sierra Nevada. All these factors in turn influence the physico-chemical processes of the water as well as as the biological communities inhabiting the rivers. Therefore, it is of particular interest to intensify control and regulation of water resources in order to minimize the negative effects of global change in these ecosystems.

High course of Dílar River.

4.2. Changes in composition and abundance of benthic invertebrate communities

Sáinz-Bariáin, M.[1]; Fajardo-Merlo, M.C.[2] and Zamora-Muñoz, C.[1]
[1] University of Granada [2] Environment and Water Agency of Andalusia

Abstract

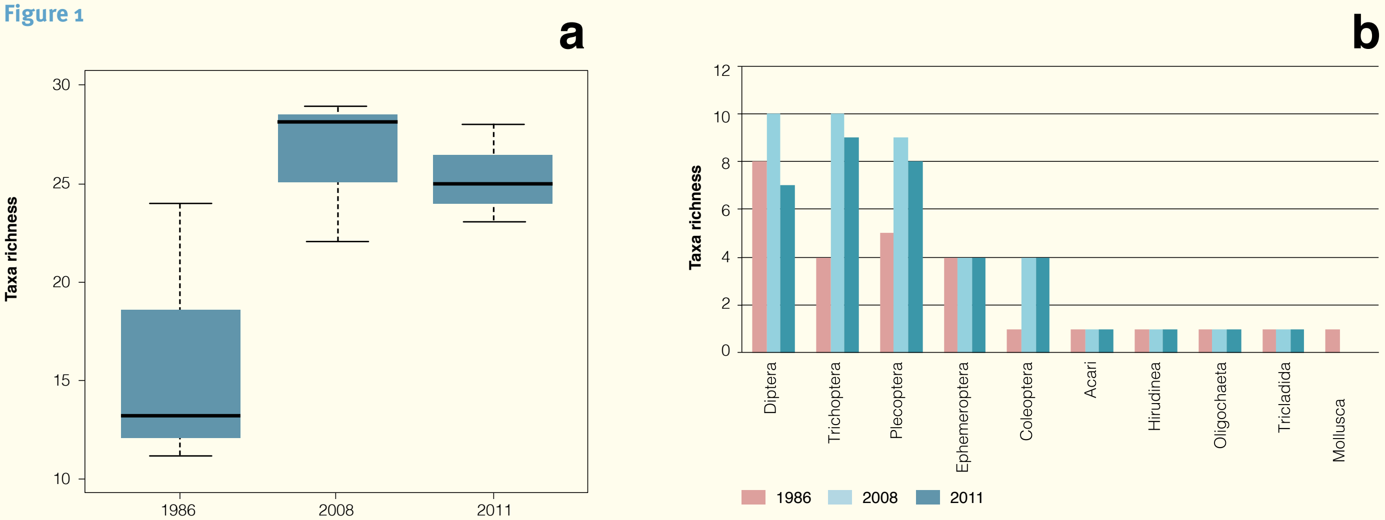
Aquatic ecosystems and the communities of benthic invertebrates that inhabit them are clearly vulnerable to the effects of environmental changes. In the present study spatial and temporal changes were detected in communities of the Sierra Nevada rivers. Local short-term alterations on the invertebrate community in relation to heavy precipitations during 2010 in the Andarax river were detected. However, long-term faunistic changes were the most noticeable when comparing recent data with those from 80's. An increase in species richness in relation to altitude was observed because species from mid-lowland reaches moved upstream. Moreover, foreign species from nearby mountain chains colonized the Sierra Nevada in the last 20 years.

› Aims and methodology

The long-term changes in species richness were studied in species of the order Trichoptera, comparing current data with those from the 1980s in the Sierra Nevada. The sampling was conducted seasonally (spring, summer, autumn) at 19 sites in 16 rivers and lakes, following the sampling and laboratory protocols to assess the ecological status of the rivers [4].

In addition, data from 2 sites (Monachil at 2150 m.a.s.l. and Monachil at 1450 m.a.s.l.) selected from 23 localties (distributed along 8 rivers) seasonally sampled since 2008 were

Figure 1



Changes in total taxa richness (p-value = 0.04) (a) and changes in taxa richness at order level in three diferent years (b) for the high-mountain site (2150 m.a.s.l.) of the Monachil River.

compared with published data in the 1990s to detect changes in benthic community [5]. Similarly, to detect short-term structural changes at community level, data from a locality of the Andarax River (1050 m.a.s.l.) were selected. In both studies, the sampling and laboratory protocols for benthic fauna in fordable rivers was followed as laid out by the General Water Authority (MAGRAMA). Moreover, adult Plecoptera and Trichoptera were collected for their species determination, using these data to detect possible changes in the spatial distribution of the order Plecoptera, given its sensitivity to environmental changes.

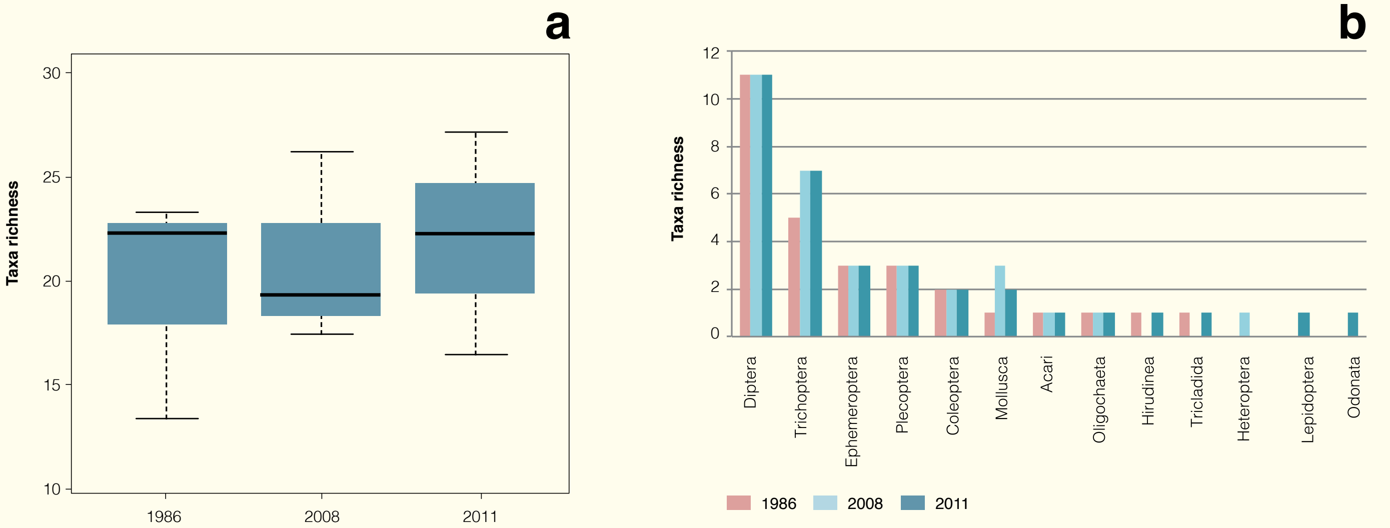
Results

In the comparative study made in the river Monachil, greater richness at the family level was found among macroinvertebrates in high-mountain elevations (2150 m.a.s.l.; Figure 1). Several taxa considered exclusive of mid-altitude mountain in Monachil River in the 1980s (*Serratella ignita* (Ephemeroptera), *Perla marginata* (Plecoptera), and *Micrasema moestum* (Trichoptera)) were captured above 2000 m.a.s.l. in current samplings. Similar results were observed in several families belonging to the orders Diptera and Coleoptera, some of which had not been captured previously in this river. In contrast, no changes in taxa richness was detected at mid-high altitude in Monachil River (1450 m.a.s.l.) (Figure 2).

Similar results were found when analysing the species richness of Trichoptera at sites situated all along the protected area of Sierra Nevada. An increase in caddisfly species richness was detected in the last 20 years (Figure 3), especially at sites situated at an intermediate altitude (1800-2000 m.a.s.l.) within the studied altitudinal range (800-3050 m.a.s.l.). Thus, most of the Trichoptera species enlarged their distribution ranges in elevation (*Rhyacophila meridionalis, Rhyacophila nevada, Hydroptila vectis, Philopotamus montanus, Hydropsyche infernalis, Micrasema moestum, Halesus tessellatus, Athripsodes* sp., and *Sericostoma vittatum*) (Figure 4) or were captured for the first time in the most recent studied period (*Agapetus* sp., *A. fuscipes, Hydropsyche pellucidula, Wormaldia occipitalis, Brachycentrus maculatum, Limnephilus obsoletus, Annitella iglesiasi, Mesophylax aspersus,* and *Athripsodes albifrons*). The species that have enlarged their distribution range are characterized by having good dispersal abilities and also inhabit mountains near the Sierra Nevada.

In the Andarax river, short-term changes in community composition were detected (2008-2012).

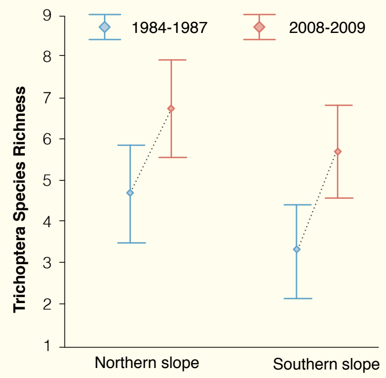
Figure 2



Changes in taxonomical richness for the medium mountain site (1450 m.a.s.l.) of the river Monachil (p-value = 0.795).
Left: Total taxa richness. Right: Taxa richness at order level.

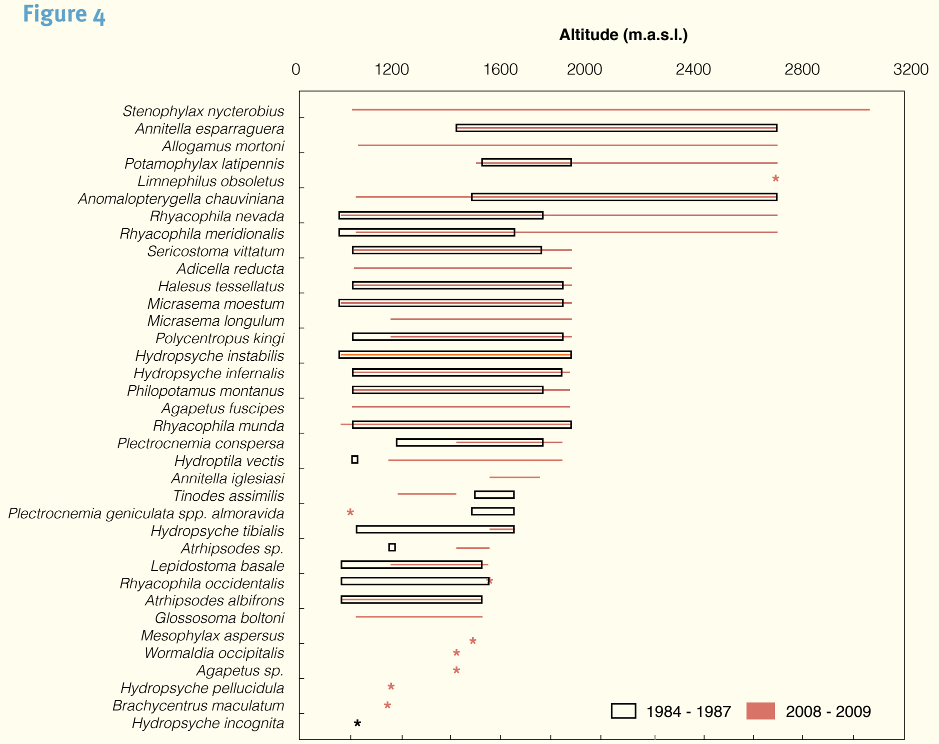
In this period, taxonomic richness diminished from 63 families captured during 2008 and 2009 to 38 in 2010. this reduction mainly affected orders Coleoptera, Odonata, Heteroptera, and Trichoptera, as well as those of the class Gastropoda. The first taxa that colonized the area belonged to the order Diptera, representing more than 90% of the individuals captured in the sampling campaign (spring) after the heavy rains. During the 2011 samplings, the number of taxa continued to be lower than in previous years (Figure 6). In the particular case of the order Plecoptera, the altitudinal comparison between benthic community current samplings and those made in 1979 and 1986, shows that several species have become rare or have disappeared at their lower distributional ranges (Figure 7). However, at high altitude, changes are hardly detected.

Figure 3



Average (± 95% CI) of Trichoptera species richness in 1984–1987 and 2008–2009 studied periods of sampling sites located at the northern and southern slopes of the Sierra Nevada streams and rivers.

Figure 4



Comparative altitudinal distribution of Trichoptera species between the two studied periods (1984–1987 and 2008–2009).

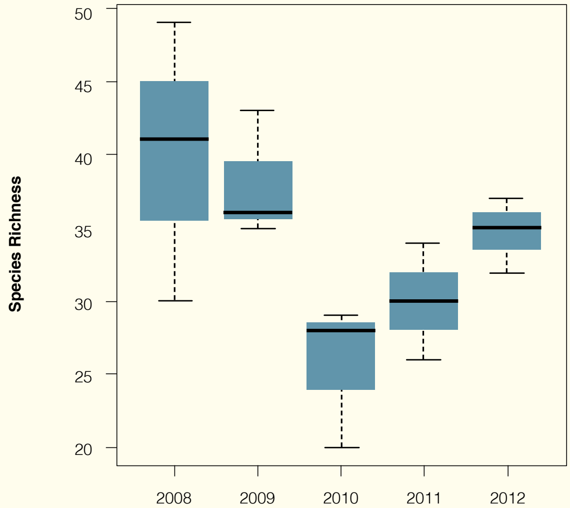
› Discussion and conclusions

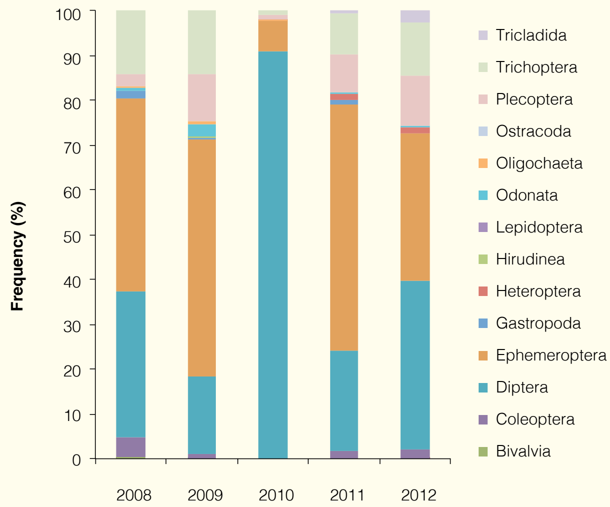
The detected relationship between altitude and change in species richness along the studied periods may be explained by the hypothesis that mountains of considerable altitudinal gradient act as refuges for species in a scenario of climate warming [6]. Species with enough dispersive ability would track thermally suitable habitats [7]. Besides sites of middle to high mountain could be suitable not only for species with narrow ecological requirements but also for generalist species. Endemic species appear to be more vulnerable as a consequence of their low dispersal capacity as well as for their strict requirements for very particular ecological conditions [8]. These species will also be threatened by more generalist species that are able to migrate in altitude and compete for resources.

These results may be relevant when considering possible conservation measures of river ecosystems from climate change. Special effort should be directed to protect conditions of lakes, headwaters, and upper reaches of streams and rivers, but also low altitude sites where human influence may be stronger. Twenty years is a short period of time to detect the effects of climate change on the overall group of species. Therefore it might be early to assess the risk to which they are subjected especially endemic species linked to the headwaters. Due to detrimet of river flow and the rise of temperatures are unavoidable, it would be necessary better control of aquatic systems in the high mountains in order to protect the species inhabiting headwaters and prevent the destruction of their habitats.

Torrential rainfall directly affect the composition and richness of the benthic community, requiring several years for some of the taxa to be collected again in the affected area. The increase in torrentiality, as a consequence of climate change, will be an additional risk factor for these communities.

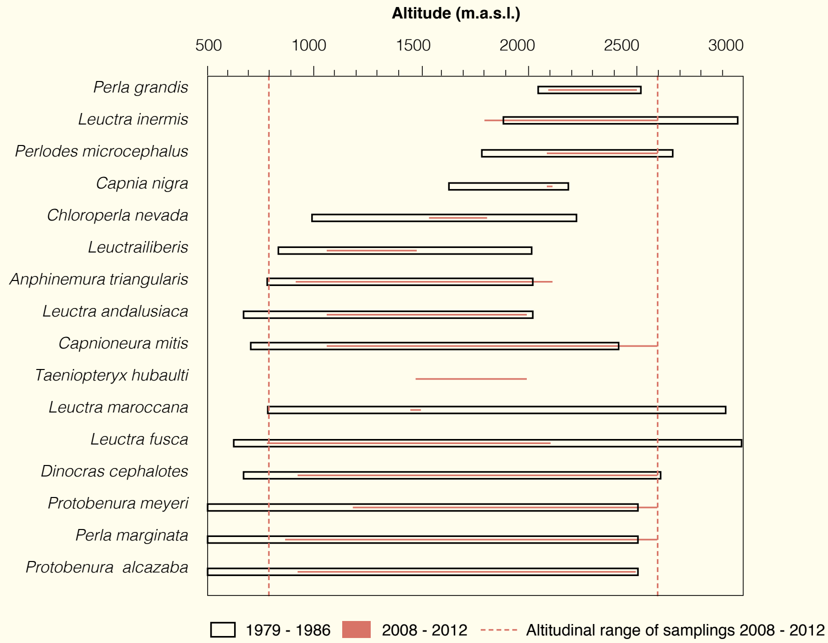
Figure 5





Changes in taxonomic richness (left) and relative abundance (right) of the benthic invertebrate community after torrential rainfall at the beginning of 2010 in the Andarax River.

Figure 6



Differences in the distribution of Plecoptera in the Sierra Nevada between 1979-1986 and 2008-2012.

4.3. Monitoring populations of common trout

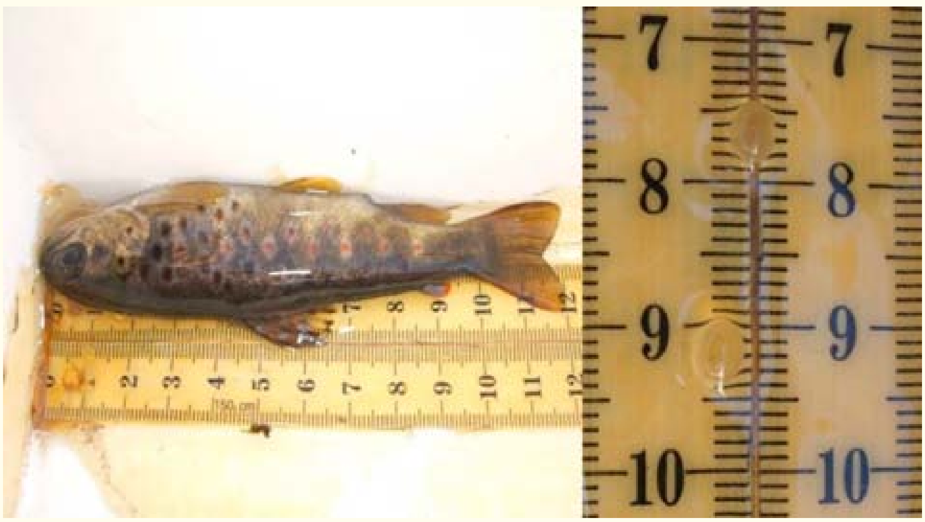
Galiana-García, M.; Rubio, S. and Galindo, F.J.
Environment and Water Agency of Andalusia

Abstract

For 9 years the common trout populations in Sierra Nevada have been monitored. During this period, symptoms of increasing and decreasing cycles have been detected in the density and biomass of the populations sampled, associated with variations in environmental factors, such as precipitation. These variations have also been detected in the other areas inhabited by the common trout in Andalusia (i.e. in the protected areas of Castril, Sierras de Cazorla, Segura y Las Villas, and in Sierras de Tejeda, Alhama, and Almijara). In several rivers of the aforementioned natural areas as well as in Sierra Nevada, very similar patterns of variation in density and biomass have also been detected, and thus the populations may be behaving similarly with respect to the environmental variations caused by global change.

› Aims and methodology

The aim is to characterise the populations of common trout in Sierra Nevada and evaluate the effect of biotic and abiotic factors on the population dynamics. As a measure for estimating the population size, the weighted maximum-likelihood method was used to calculate the probability of capture and the standard error. The age was determined by growth equations and examining the scales to verify the population structure by mathematic models. Biomass was considered as the mean weight of the specimens captured. The precipitation was determined using the data of hydrometereological years of Environmental Information Network of Andalusia (REDIAM) and the Watershed function of ArcGIS 9.3 to establish the watershed basins. The reproductive phenology was monitored by abdominal massage of the specimens captured in different periods of the year, noting the formation of eggs or sperm for each individual without making a significant extraction of the reproductive material. More details on the methodology followed are available elsewhere [9].



Smallest mature female captured during the samplings: a specimen 12 cm long with eggs 4 mm long.

Results

The results for density and biomass of the common trout during the study period show that at most of the census stations, there was a descending trend until the year 2008 (Figure 1). From 2009 on, the density and biomass values in general increased, with the exception of 2010, when the torrential rains substantially altered the common trout habitats, as reflected in the values of these parameters.

The increases in the density values of the years 2011 and 2012 were due mainly to the great number of hatchlings sampled in the census stations, often constituting the greatest recruitment during the entire sampling period.

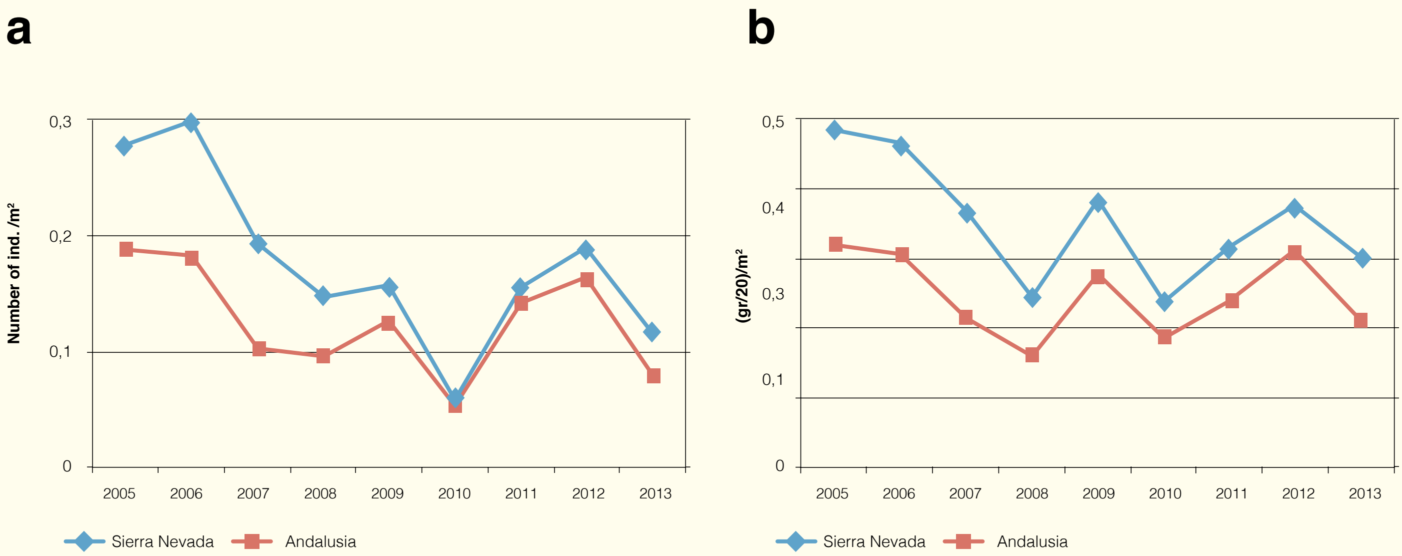
The variations in density were compared with the different annual precipitation values (for which data from hydrometeorological years were used), detecting correlations between the density values of the common trout and changes brought about by periods of drought and high precipitation, which significantly altered the population size (Figure 2). Torrential precipitation has direct effects both on trout populations as well as on macroinvertebrate numbers (see Chapter 4.2), strongly diminishing population density.

After these periods of torrential rains (e.g. 2010), as occurs with aquatic macroinvertebrate communities (see Chapter 4.2), the common trout recovered in the year after these periods of heavy precipitation. In addition, the lower precipitation values, as in 2012, significantly affected the number of hatchlings, as detected in samplings of 2013.

With respect to the age classes captured, the general trend was for the populations to have a low number of adult specimens, these being absent from many samplings (Figure 3).

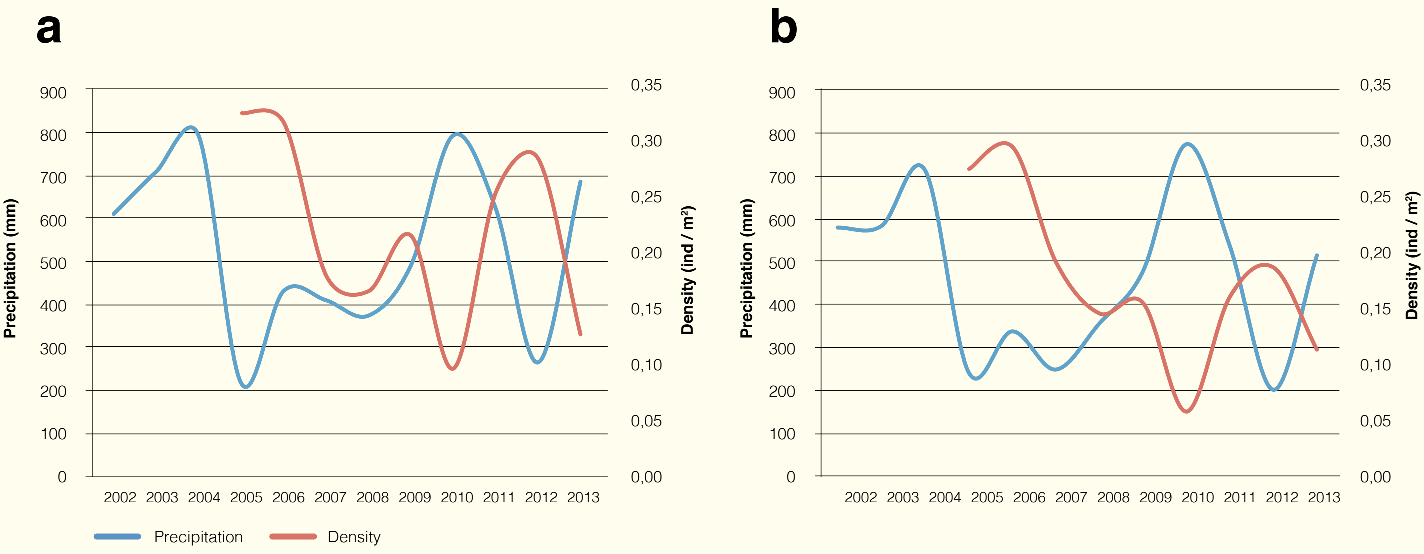
Generally, the common trout reproduces in autumn or winter—the higher the latitude and elevation, the earlier in the year, due to low water temperatures and longer incubation periods [10, 11]. In its natural distribution area, the average date of spawning occurs at the beginning of October in Finland or Norway [12], and in February in southern populations such as Asturias [13] or Granada [11] (Spain). In the river Castril (Granada province), the reproduction period is very long (5 months), the last nest being constructed at the beginning of April [11] (Figure 3). In works conducted in Sierra Nevada, reproductive specimens have been detected, some even of small size, from the month of October to the first two weeks of May.

Figure 1



Densities (a) and biomass (b) of common trout in Sierra Nevada (blue line) and in the overall region of Andalusia (red line) (Fishing Census from Regional government).

Figure 2



Evolution of the trout density (red line) and precipitation (blue line) in Sierra Nevada (a) and Andalusia (b). (hydrometeorological years)

Discussion and conclusions

The greatest densities and biomass in Andalusia have been located in Sierra Nevada, in the Guadalfeo and Genil basins. Of all of the populations sampled, only the populations of the rivers Chico de Soportújar and Lanjarón can be considered abundant in terms of biomass, evidencing the delicate state of this salmonid in Andalusia.

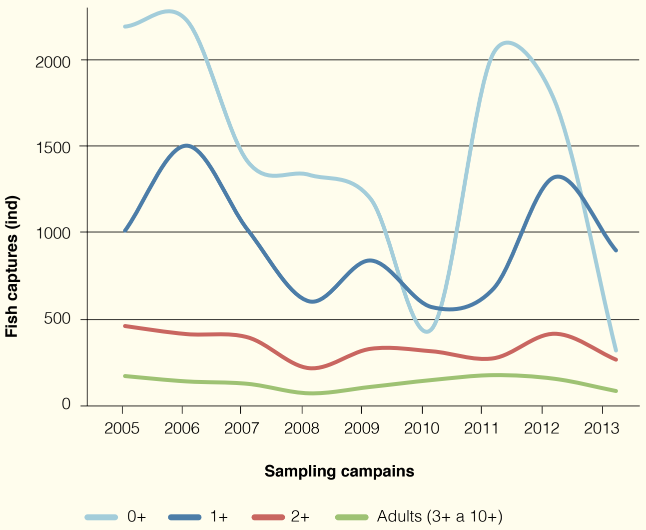
Furthermore, several river courses are subjected to drying phenomena due to hydroelectric diversions (Dílar, Monachil) and irrigation channels (Bérchules, Chico de Soportújar, Torrente, Trevélez, Andarax, Mecina), implying a grave threat to the common trout populations in these rivers.

The relation detected between the annual rainfall regime and the variations in the density of the common trout populations implies that this species is very sensitive to environmental variations, as demonstrated by the influence of droughts and torrential rains in the number of specimens detected in the samplings. After the phenomena of torrential rains, which can inflict abrupt declines in the communities sampled, the populations recuperate almost immediately. This is probably due to the adaptation of the trout populations to these rather common phenomena in Sierra Nevada.

However, despite the detection in 2011 and 2012 of a great number of hatchling and juvenile trout, in many of the sampling stations the numbers of adult specimens have been low during the entire census period, the age structure being strongly unbalanced, with a strong predominance of classes 0+ and 1+. The low availability of refuge for adults during certain periods of the year appears to constitute the most important part of this limiting factor, although other factors such as droughts determine the scarcity of adults.

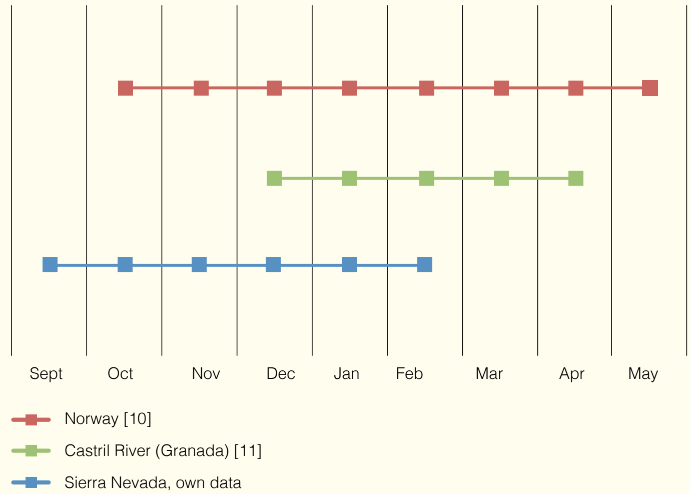
As described above, the reproductive period of the trout in Sierra Nevada is longer than any other described in the scientific literature (Figure 4). As suggested by other authors [11], this long reproductive period offers an advantage in a highly unpredictable hydrological regime, such as that of Sierra Nevada.

Figure 3



Graph of number of captures (expressed by age classes) of the common trout from the year 2005. Over the sampling period the hatchlings captured constitute a mean of 50.3% of the captures. Around 32.8% of the captures correspond to juvenile specimens, and the remaining 16.9% to adults. Of the adult specimens, some 71.7% were in the age class 2+, and thus captures of age 3+ or older are rare (only 4.8% of the total captures).

Figure 4



Spawning periods of the common trout

Salmo trutta

4.4. Sentinels of global change (I): mixotrophic algae in La Caldera Lake

Medina-Sánchez, J.M.; Delgado-Molina, J.A. and Carrillo, P.
University of Granada.

Abstract

Primary producers of high-mountain lakes of Sierra Nevada (such as La Caldera) are dominated by microalgae with a mixotrophic metabolism, which gives them an adaptive advantage in an environment subjected to ultraviolet-radiation stress and extreme oligotrophy. This dominance determines the entire structure and mode of functioning of its planktonic communities. However, recently, increased seasonal presence and persistence of microalgae with a strictly autotrophic metabolism were observed. The results of an *in situ* experimental design simulating the growing input of allochthonous nutrients associated with aerosols of Saharan origin indicate that greater phosphorus concentrations trigger dramatic changes in the algal community. These changes imply the loss of the mixotrophic compartment, which is displaced by an explosive development of an algal community of very low diversity, dominated by strictly autotrophic species resistant to ultraviolet radiation and that can even become detrimental to the heterotrophic microbial food web and herbivorous consumers. These processes of eutrophication could, by growing intensity, affect these lakes, which function therefore as excellent sensors of global change.

› Aims and methodology

The experiments were performed *in situ* with 10 mesocosms (bags 1 m in diameter, 7 m deep, and 2,700 litres in capacity), containing water taken from the mixed layer of the lake. The mesocosms were made of polyethylene, which transmits the entire spectrum of solar radiation (transmittance: ~60% at 280 nm and >80% at 700 nm of wavelength). The complete factorial experimental design (5x2) consisted of: (i) 5 levels of P enrichment twith increasing final concentration (no addition [control], 20, 30, 40, and 60 µg P L^{-1}) and with NH_4NO_3 to a N:P molar ratio of 30 to avoid the limitation of the organisms by N; (ii) two levels of solar-radiation quality (presence and absence of ultraviolet radiation) covering half of the mesocosms with a layer of Plexiglas that excluded the ultraviolet radiation (treatments with absence of UVR). After the pulse of nutrients, the mesocosms were incubated *in situ* for 70 days. The periodicity of the sampling of the mesocosms was adjusted to the generation times of the different organisms studied (bacteria, phytoplankton, zooplankton). The analytic methodology followed to quantify the different response variables (physico-chemical and biological) are detailed elsewhere [14].

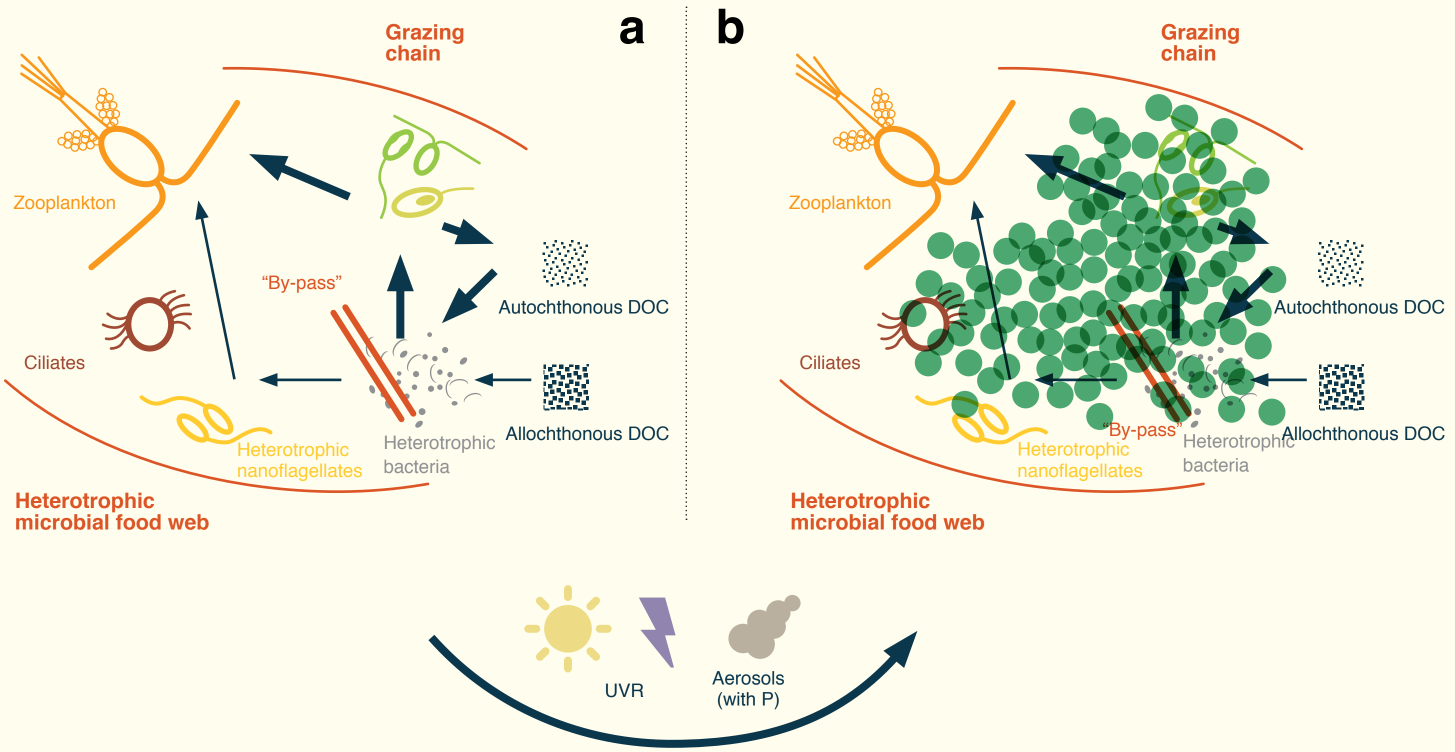
› Results

The structure and functioning of the pelagictrophic web of lake La Caldera is governed by the dominance (among the primary producers) of a community of unicellular flagellated microalgae capable of combining the phototrophic capacity (photosynthesis) with the heterotrophic one (e.g. ingestion of bacteria by phagotrophy). This mixed modality of nutrition, called mixotrophy, proves advantageous under these conditions of extreme oligotrophy and of stress by ultraviolet radiation (UVR) by establishing a complex regulation between the mixotrophs and bacteria, poetically called "*neither with you nor without you*" [15]. Thus, the bacteria are submitted to a strong control by algal predation ("*with you I die…*"), which capture "expensive" minerals packaged as bacteria, at the same time as the bacteria depend on "cheap" organic carbon fixed and excreted by the algae ("*without you I cannot live*"). As a result, the predatory capacity (phagotrophic) of the mixotrophs acts as a *bypass*, favouring the flow of energy and nutrients towards the herbivorous consumer chain. The mixotrophs occupy the ecological niche of the heterotrophic microorganisms, resulting in little development of the heterotrophic microbial food web (bacteria, flagellates, and heterotrophic ciliates), a singular characteristic of high-mountain lakes of Sierra Nevada (Figure 1a).

A time series between 1975 and 2010 revealed an increase of abundance and seasonal persistence of algae with strictly autotrophic metabolisms (only photosynthesis). With respect to the question as to whether this tendency might be due to the greater atmospheric transport of nutrient-rich aerosols observed recently [16], the results of a complex experimental design (mesocosms incubated *in situ* in La Caldera lake, simulating scenarios of current and future inputs of allochthonous nutrients associated with Saharan aerosols [17]), underscored the key role of these P inputs capable of generating marked changes in the algal community. The P pulses provoked the explosive development of only one species (a strict autotroph) of rapid growth and UVR tolerance (*Dictyosphaerium chlorelloides*), which displaced a more diverse community of mixotrophic algae and diatoms (Figure 1b), resulting in a sharp descent in the algal diversity (Figure 2) [18] and the total collapse of the heterotrophic microbial food web (Figure 1b).

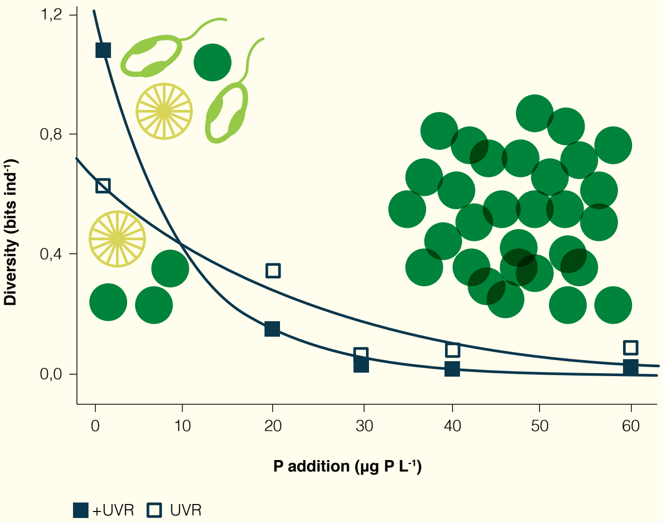
Figure 1

An oligotrophic high-mountain lake



(a) Diagram of the planktonic structure and the carbon flow (black arrows with thickness proportional to the flow) between their components present in high-mountain lakes. Modified from [15]. (b) Changes in the structure of the trophic network after the pulsed input of mineral nutrients associated with the atmospheric aerosols. Modified from [14]. DOC: Dissolved organic carbon. UVR: Ultraviolet radiation. P: phosphorus.

Figure 2



Variation in the diversity index (*Shannon–Wiener*) of the algal community in the experimental treatments. The markers represent mean diversity values; the curves represent the non-linear regression lines (exponential model). Modified from [18].

Figure 3

La Caldera lake thawing.

Discussion and conclusions

The experimental results evidence that increases in pulsed nutrient inputs cause the development of a simplified algal community with very low diversity, due to the predominance of one or few species of strict autotrophs which are resistant to UVR and which can reach densities of up to three orders of magnitude greater than in the unaltered ecosystem.

These results suggest a link between the greater seasonal presence and persistence of strictly autotrophic algae observed in recent years and the trend in the increase of the atmospheric transport of Saharan aerosols. The accentuation of this trend with global change may lead not only to the loss of taxonomic and functional biodiversity but also to the loss of an entire functional group characteristic of these lakes (mixotrophic algae), a collapse of the heterotrophic microbial food web, and even a negative impact on the development of the higher trophic levels, such as herbivorous zooplankton (see Chapter 4.5).

4.5. Sentinels of global change (II): herbivorous consumers in La Caldera Lake

Villar-Argaiz, M.[1] and Bullejos, F.J.[2]

[1] University of Granada [2] University of Oslo

Abstract

High-mountain lentic systems, because of their remote and ultraoligotrophic nature, are optimal sensors for the impact of global change. Long-term physico-chemical and biological records of La Caldera Lake span more than three decades of uninterrupted study, beginning in 1975. Now these type of ecosystems have become sentinels of global change in Sierra Nevada. These records are complemented with extensive satellite data that, like the aerosols (TOMS-NASA), enable the successful quantification of the frequency and intensity of atmospheric events.

Over the last few decades, the frequency and intensity of the fundamentally Saharan aerosol intrusions affecting Sierra Nevada have increased. The fertilizer effect of the atmospheric dust is reflected in the linear increase in phytoplankton, but not of their herbivorous zooplankton consumers, which have decreased under high quantities of food. To test the effect of allochthonous nutrients, large mesocosms (3000 liters) were incubated in situ for 70 days, to which increasing quantities of nutrients were added mimicking natural aerosol intrusions. Consistently with the long biological records for the studied lake, we observed that moderate nutrient inputs stimulated the growth of algae and consumers. However, large inputs (>20-30 μg P L^{-1}) decreased the growth of herbivore consumers, resulting, due to their fertilizing effect, in decreased transparency and quality of the water.

Aims and methodology

The aim is to characterise the trends of aerosol deposition in La Caldera lake, as well as its impact on the herbivorous consumer populations in this lake.

Teledetection by satellite

The aerosol index (AI), developed by NASA as a proxy for the deposition of inorganic P, was used. The AI index was calculated from the irradiance measurements of TOMS (Total Ozone Mapping Spectrometer) of the satellites Nimbus 7 (1978-1993) and Earth Probe (1996-2004) of NASA, determined for the closest coordinates to La Caldera Lake (37.5°N; 3.075°W).

Annual biological monitoring of La Caldera Lake

The phytoplankton and zooplankton samplings began in 1973 and 1975, respectively. Although the time series are not complete, the lake was sampled a minimum of 4 and a maximum of 15 times yearly. The abundance and biomass of the phytoplankton and zooplankton were estimated according to standardized protocol described elsewhere [19, 20].

Experimentation in situ

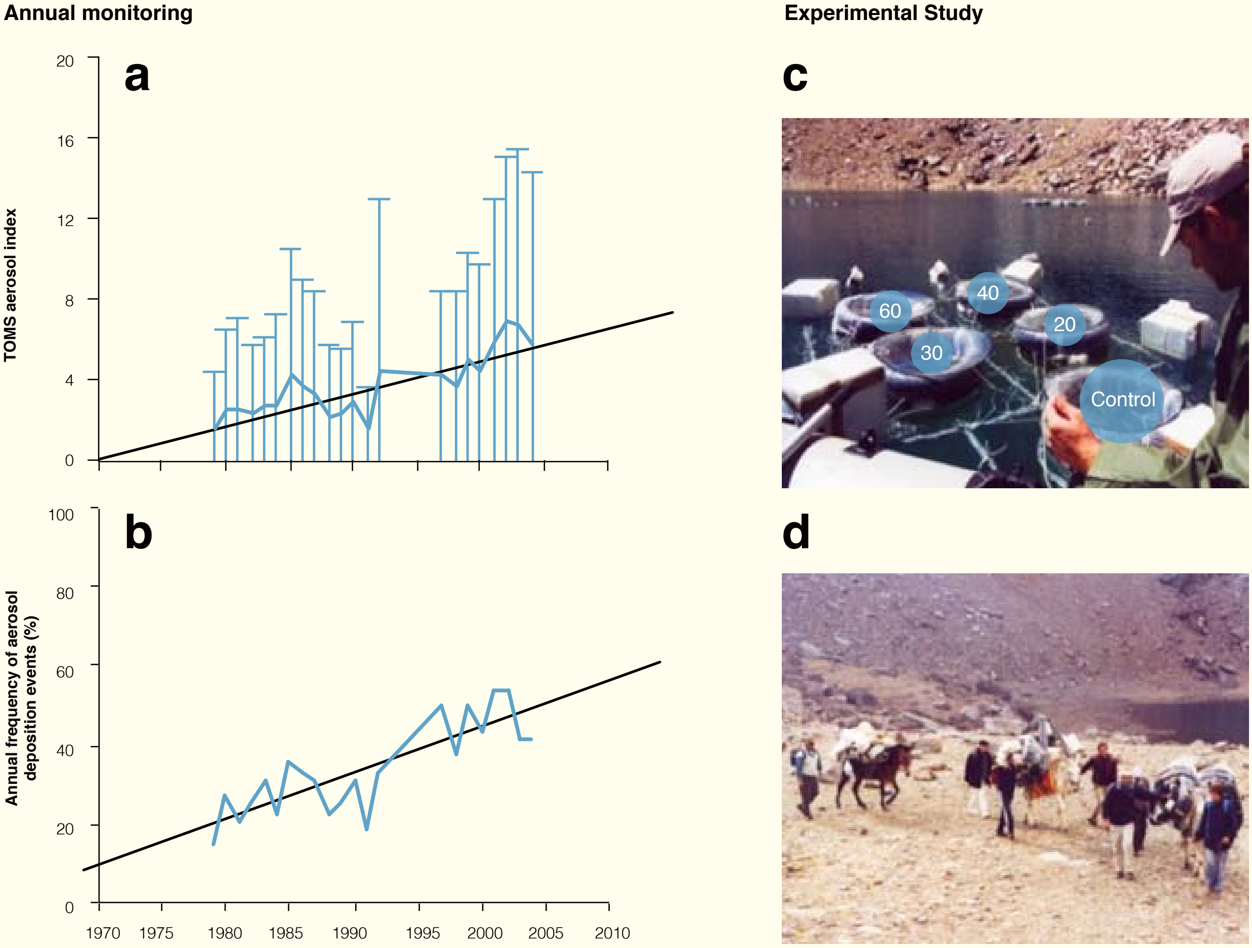
The experiment consisted of suspending polyethylene bags (0.7 m diameter x 7 m long) from a platform anchored in the area of maximum depth of the lake (Figures 1 c and d). The enclosures received ascending quantities of P (NaH_2PO_4), constituting the addition treatments (20, 30, 40, and 60 μg P L^{-1}), except the enclosure control without P addition (0 μg P L^{-1}), which simulated the conditions of the lake. The concentration of the nutrients added in the most enriched treatment (60 μg P L^{-1}) was similar to the maximums recorded for aerosols detected in Sierra Nevada [21]. Over the 70 days of incubation, periodic samples were taken to determine the biomass of the phytoplankton and zooplankton as described above for the biological monitoring of the lake.

Results

Annual monitoring

The analysis of the series of atmospheric data from NASA indicates that over the last few decades (1978-2004), the content of aerosols from the troposphere has increased in the area of Sierra Nevada, and particularly since 1990. During this period, the magnitude of aerosols (TOMS AI) has grown five-fold (Figure 1a), while the frequency of these atmospheric events has increased three-fold (Figure 1b). From the biological standpoint, the positive relation of the intensity and frequency of aerosol intrusions with respect to the biomass of phytoplankton (Figures 2a and b) indicates that the aerosols provide nutrients that can become fertilizer for these ultraoligotrophic systems. The comparative analysis of the population dynamics over the last three decades indicates a temporal change in the phytoplankton-zooplankton relation. While the biomass of the zooplankton remained greater than that of the phytoplankton until the mid-1990s, the phytoplankton became dominant thereafter, coinciding with the increase in aerosols and giving rise to a strong uncoupling in the primary producer-herbivorous consumer relation (Figure 3a). Consequently, the annual relation between the phytoplankton and the zooplankton biomass was not linear but rather unimodal with a maximum of zooplankton at around 100-150 µg of fresh weight of phytoplankton per litre ($y = -0.009 x^2 + 2.285 x$, $p < 0.05$; Figure 3b).

Figure 1

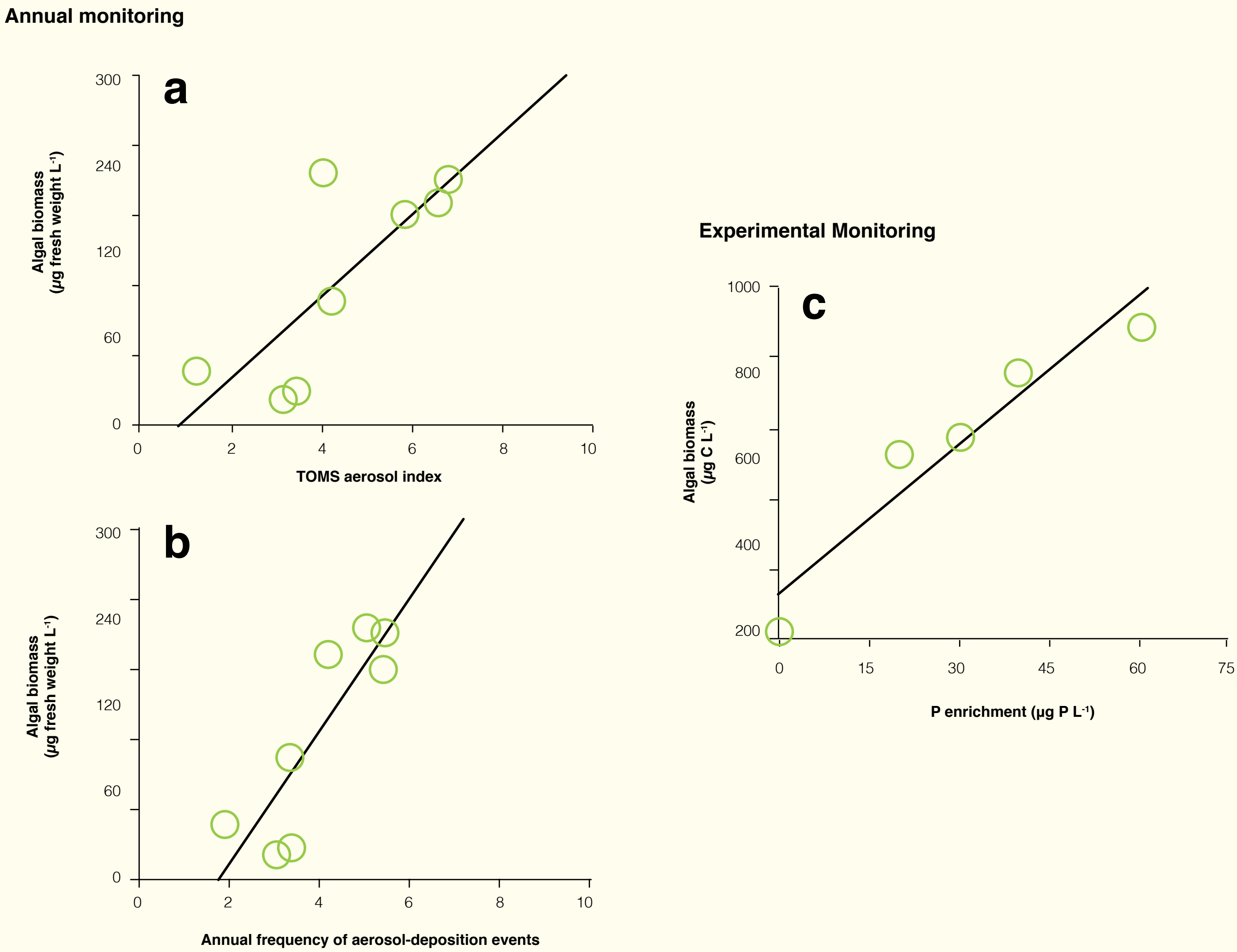


Annual dynamics of (a) TOMS aerosol index and (b) annual frequency of aerosol-deposition events (TOMS-NASA). (c) Aspect of the experimental mesocosms in La Caldera Lake in 2003 and (d) the transport of materials for the experiment.

Experimental study: mesocosms

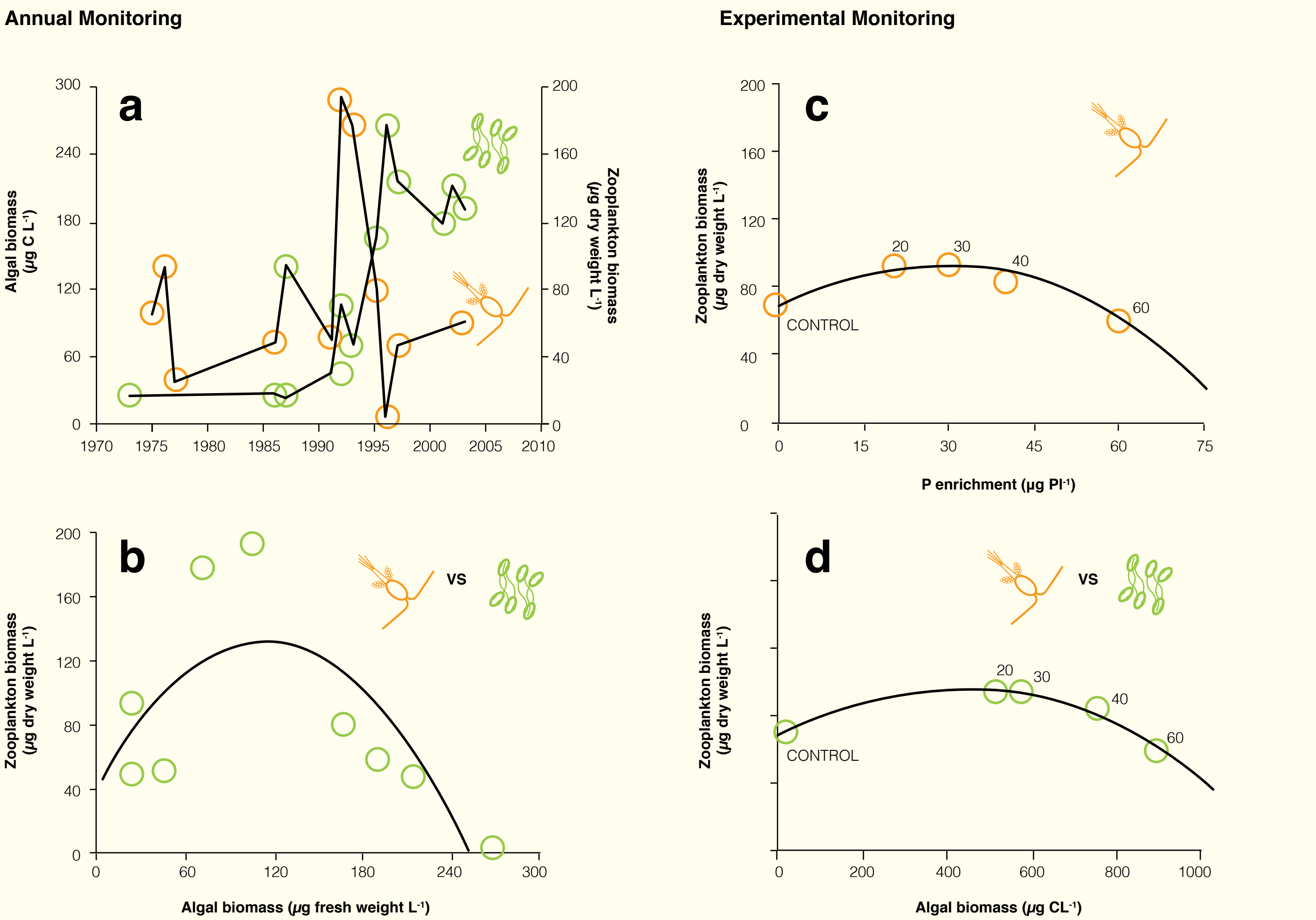
The effect that nutrients adsorbed onto aerosols could exert on natural biological communities was tested experimentally in La Caldera lake in the year 2003. The experimental enrichment with nutrients increased the algal biomass in a linear way (Figure 2c). On the contrary, the response of the herbivorous consumers to the enrichment was not linear but rather unimodal (Figure 3c). As a consequence, the zooplankton biomass augmented parallel to that of the phytoplankton to an intermediate threshold of enrichment (treatments 20 and 30; Figure 3d) beyond which the zooplankton decreased, coinciding with a greater abundance of phytoplankton.

Figure 2



Relations between the algal biomass and (a) TOMS aerosol index and (b) the annual frequency of deposition events. (c) Relation between the algal biomass and the enrichment in phosphorus in the experimental mesocosms of 2003.

Figure 3



(a) Temporal dynamics of the populations of algae and zooplankton in La Caldera Lake (historical series from 1973 to 2004). (b) Relation between algal and zooplankton biomass in La Caldera Lake. Relations between zooplankton biomass and (c) P enrichment and (d) algal biomass in the experiments of 2003.

Discussion and conclusions

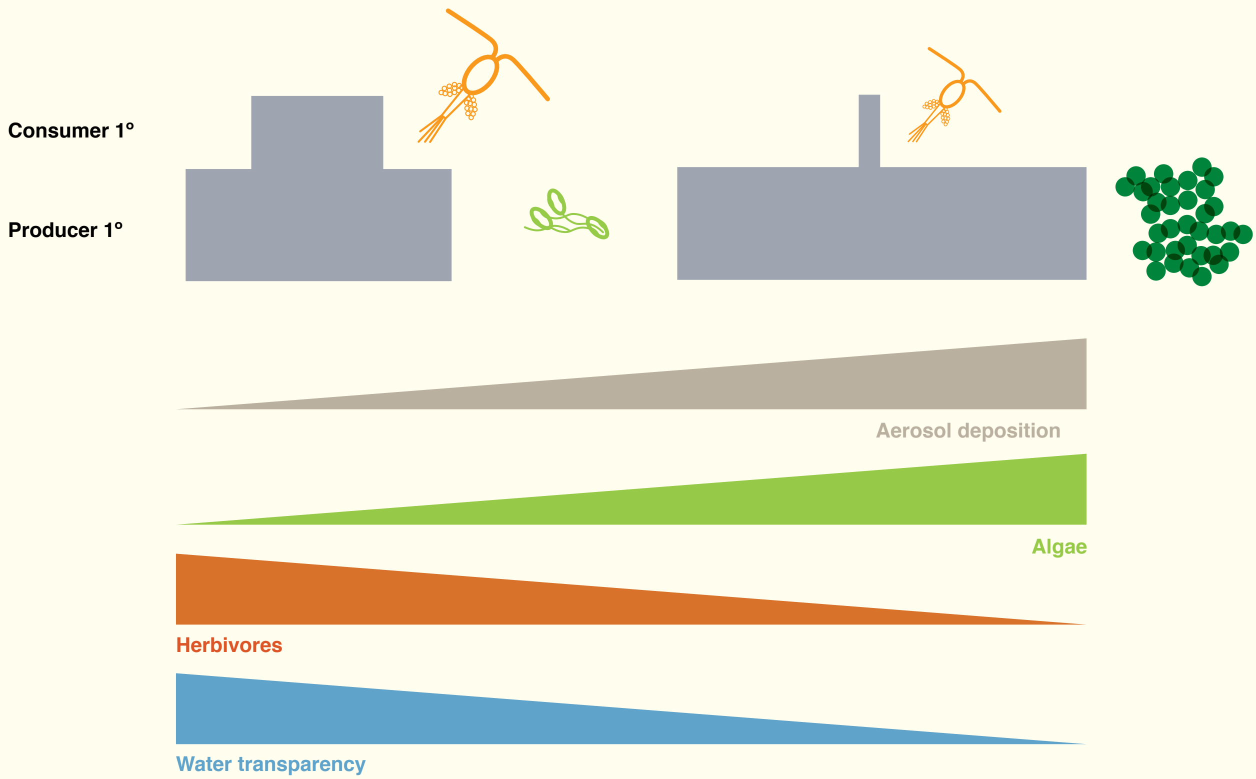
The long-term monitoring of the population dynamics of pelagic plankton of La Caldera Lake indicates that the autotrophic phytoplankton has increased in parallel with the greater intensity and frequency of atmospheric aerosols. These results suggest that the allochthonous nutrients associated with Saharan intrusions exert a fertilizing effect that stimulates the growth of algal biomass. These patterns coincide with previous findings indicating that Saharan depositions constitute major sources of nutrients, particularly P [21], which favour the increase in chlorophyll in the oligotrophic waters of high-mountain lakes of Sierra Nevada [19], the Alps [22], or the Mediterranean Sea [23].

The deposition of atmospheric N, both in the dry form and as acid rain, has received special attention due to the growing use of fossil fuels and the intensification of agriculture. However, the geographic position of Sierra Nevada, under the influence of winds from the Sahara, has caused the aquatic high-mountain systems to receive more P than would be expected in other types of Alpine lakes of Central or Northern Europe. Although these systems are chiefly P limited, it has recently been proposed that the P input associated with Saharan intrusions may even cause a change in the mineral limitation from P to N in these systems. However, regarding life in a more dustier world, what effects could this cause on the rest of the trophic chain? To resolve this question, it is indispensable to trace the effects that inputs of nutrients adsorbed onto atmospheric dust might exert on the consumers of primary producers.

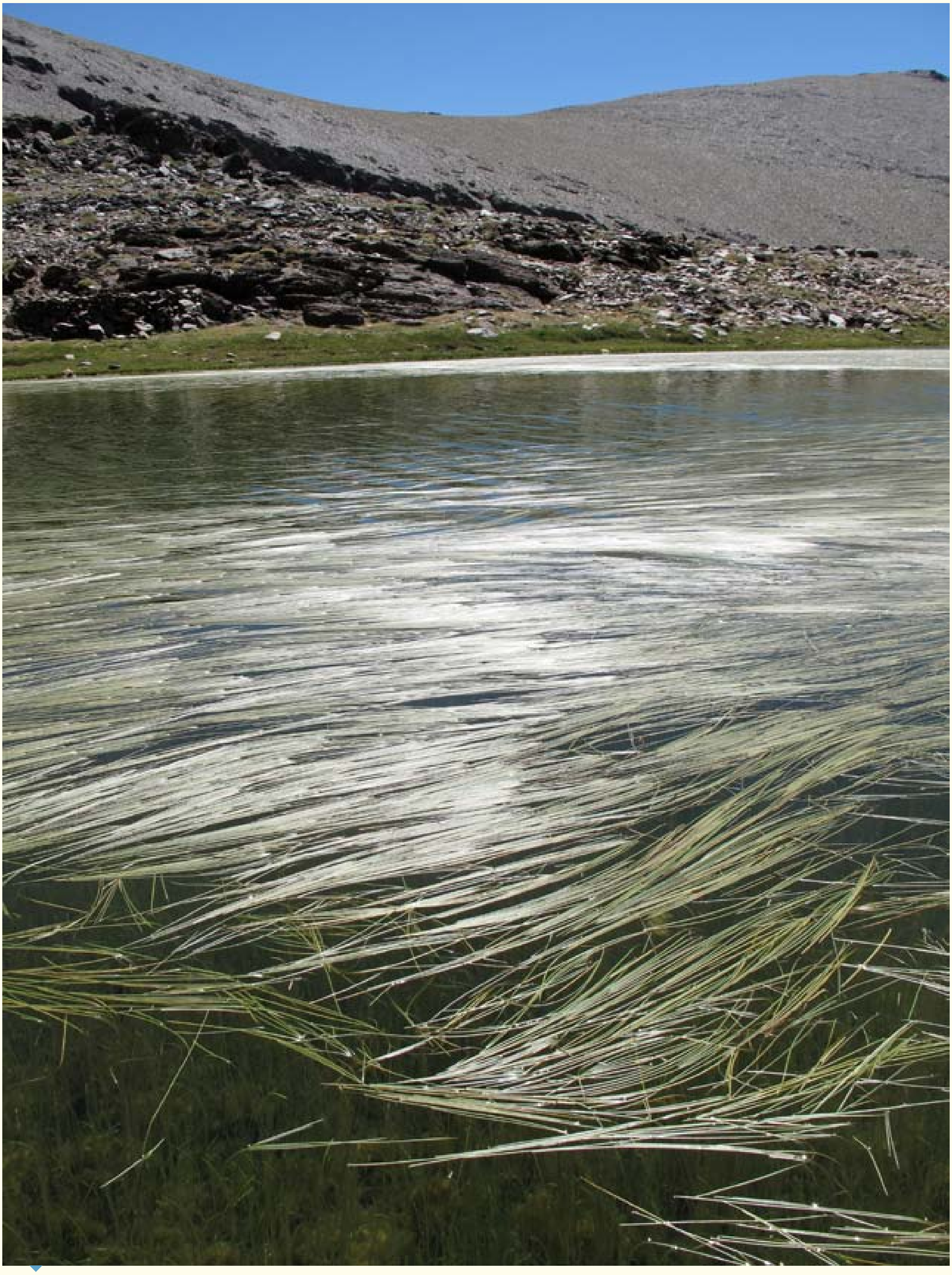
Both the natural observations as well as the experiments conducted in La Caldera Lake indicate that the Saharan intrusions do not reinforce the bottom-up control of the system. That is, algal growth does not favour the development of herbivores. On the contrary, if, as has been demonstrated experimentally, the dominant herbivorous consumer in these systems (the copepod *Mixodiatomus laciniatus*) cannot control the proliferation of algae, these could accumulate in the system, resulting in an undesired fertilization that deteriorates the final trophic state of the systems (Figure 4).

In short, the atmospheric processes affecting the territory have far-reaching repercussions that can affect the trophic state of the ecosystems by altering the nutrient cycle and reducing the efficiency at which energy and matter transfers throughout the trophic chain. These studies underscore the importance of continuing with long-term monitoring programmes (LTER-Spain) in high-mountain lentic systems, which for their remote and ultraoligotrophic nature are optimal sensors of the impact of global change.

Figure 4



Representative scheme of the effects of increased Saharan intrusions on the trophic network of a pelagic aquatic system, favouring algal proliferation, diminishing herbivore biomass and water transparency.



Lakes of glacial origin represent very sensitive ecosystems that respond rapidly to changes in the surrounding environment. Laguna de Juntillas (2.930 m).

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› *More references at http://refbase.iecolab.es/ref_dossier_resultados.html"*

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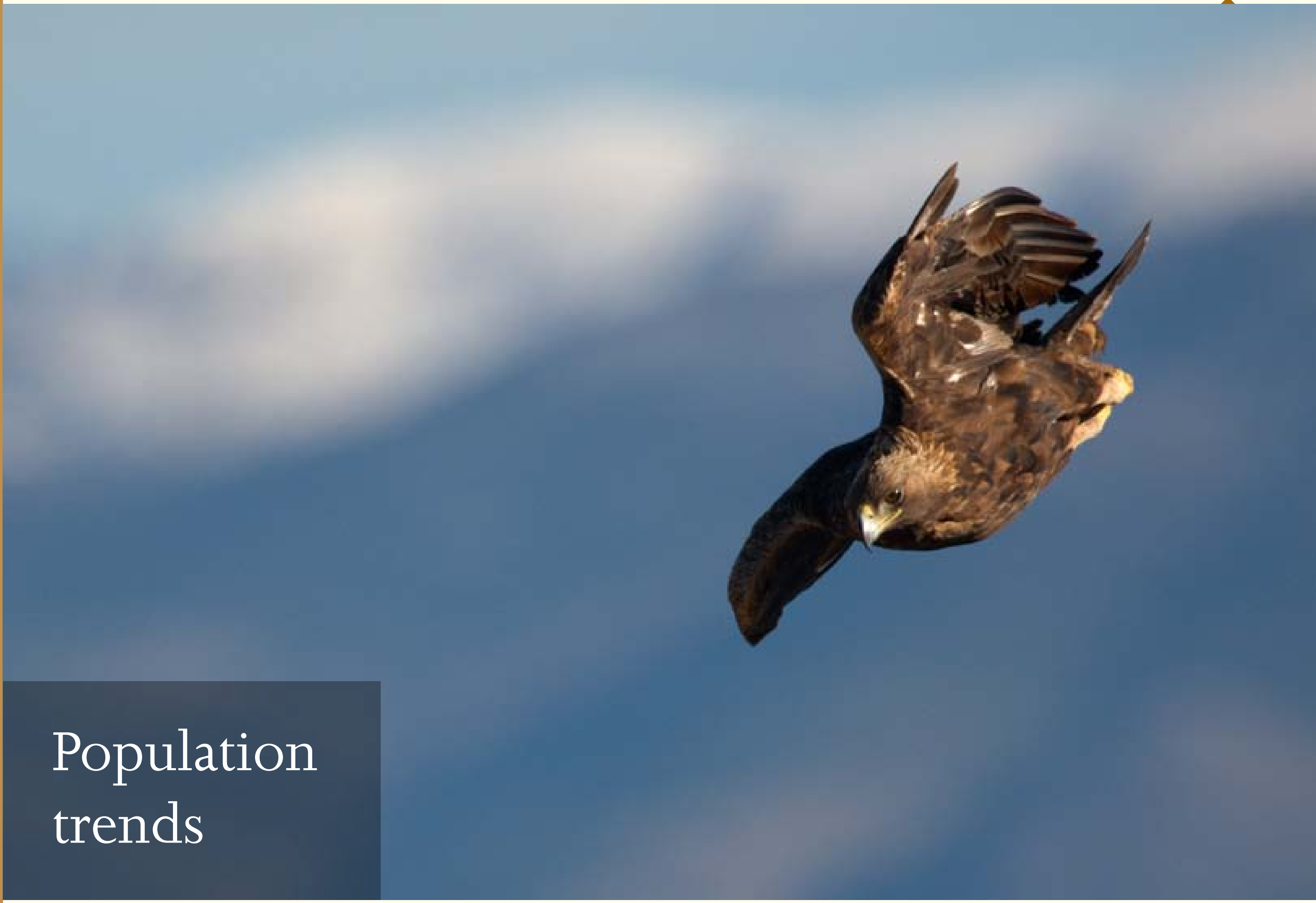
Chapter 5

The golden eagle is one of the most emblematic raptors in the Mediterranean high mountain.

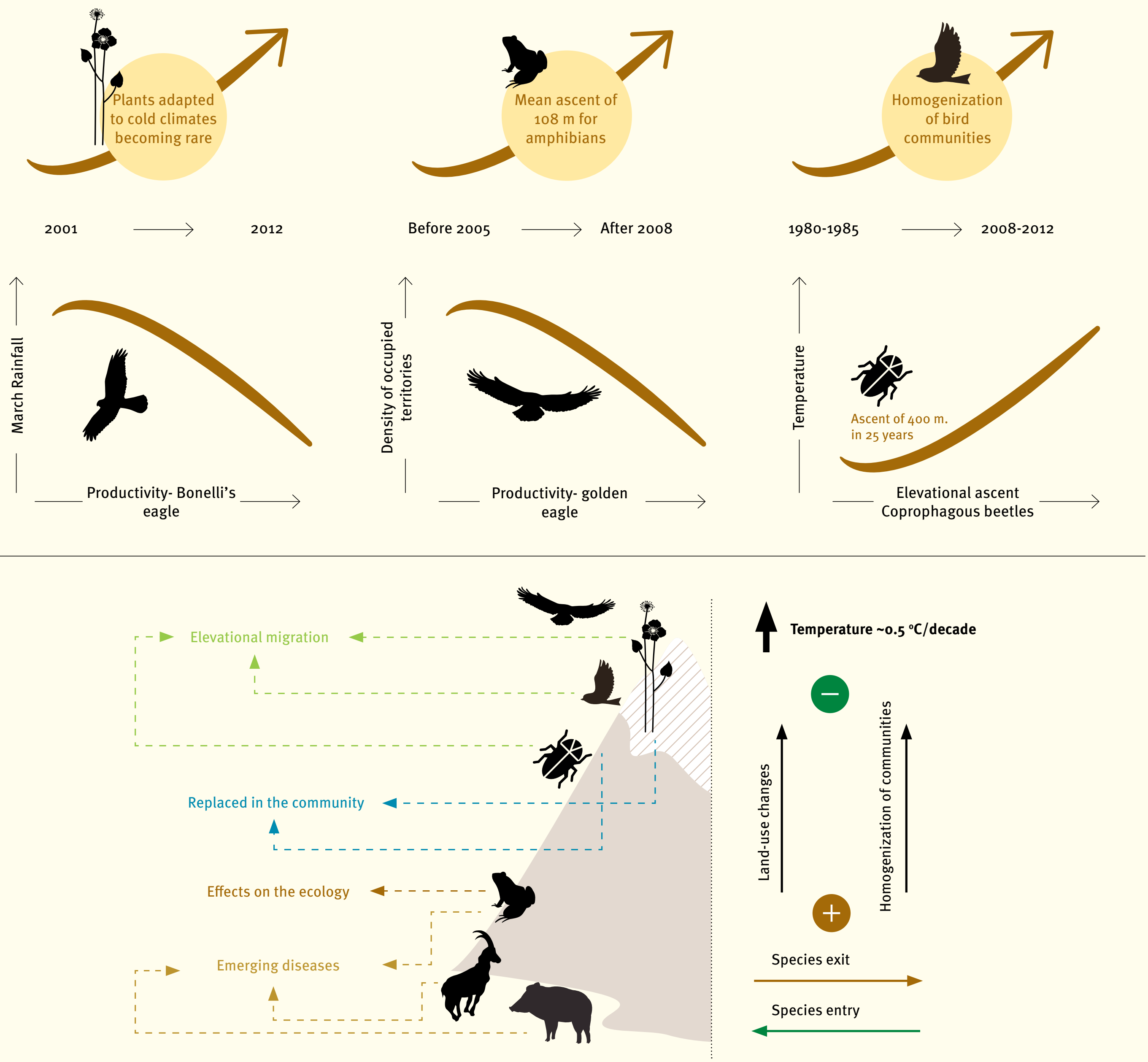


Population trends

Changes in the distribution and abundance of the populations of plant and animal species constitute a clear response to environmental alterations. Therefore, the monitoring of population trends is an essential tool to evaluate the adaptation capacity of species within a context of global change. In the present chapter, several study cases are reviewed concerning changes in the distribution and abundance of plant and animal species in Sierra Nevada. One of the most common patterns (in Sierra Nevada and other mountain systems) among different taxonomic groups consists of an elevational displacement towards higher elevations. For insects, this elevational migration has been confirmed for coprophagous beetles. The results have shown that in a span of 25 years, 89% of the species ascended in mean elevation and their upper distribution limits while somewhat more than 84% expanded their lower distribution limits. For instance, *Bubas bubalus* has climbed no less than 1200 m in 25 years (~50 m/ year). The mean elevational ascent was 400 m, which coincides with an upward move of the same magnitude in the Apollo butterfly of Sierra Nevada. In the case of Hymenoptera, at least two species of formicids have also been found to ascend elevationally (*Proformica longiseta* and *Formica fusca/lemani*), which expanded their upper distribution limits by some 200 m on the southern slope of Sierra Nevada.

Among vertebrates, equivalent responses have also been confirmed. Mountain passerines have shown a marked temporal dynamic over the last 30 years. Some generalist mountain species are now more abundant than before in high-mountain areas, while the most typical alpine species become progressively more scarce.

Amphibians also appear to have changed their distributions over the last 30 years, especially the common frog.



Graphical summary of the main results described in this chapter. It shows temporal trends of biotic variables, relationships among variables and a schematic representation of the main repercussions of the global change on the biodiversity of Sierra Nevada.

The high-mountain vegetation also follows the same pattern and in only 11 years three species have moved upwards in elevation: *Plantago radicata* subsp. *granatensis, Pilosella castellana,* and *Eryngium glaciale*. On the other hand, the study of plant communities of the summits shows a progressive increase in plant cover. This phenomenon is especially evident below 2900 m.a.s.l., while above this level the trend is stable at the currently and even tends towards a slight descent.

These results indicate that the protected mountain areas play a fundamental role in maintaining biodiversity in a context of global change, since populations can adapt to the changes, moving elevationally according to their ecological needs.

5.1. High-mountain plant communities: GLORIA

Sánchez-Rojas, C.P.[1] and Molero-Mesa, J.[2]
[1] Environment and Water Agency of Andalusia [2] University of Granada

Abstract

The main findings are presented for the monitoring of vegetation in the high summits of Sierra Nevada over the last 11 years within the project GLORIA (*Global Observation Research Initiative in Alpine Environments*). The results show changes in the cover of the taxa that are more pronounced in certain orientations and/or elevations. The plant cover increases more at southern orientation and lower elevations (‹3000 m a.s.l.), while a decline has been found on the eastern orientation. A replacement has been detected in the communities, with the loss of taxa such as *Luzula hispanica* and *Poa minor nevadensis*, which are often linked to conditions of greater moisture, indicating a change in water availability. Results from the whole of Europe in the period 2001-2008 indicates that cool-climate plants disappear from the high mountains, while those adapted to heat prosper. However, a later review for Sierra Nevada appears to indicate a reversal in this trend.

› Aims and methodology

Four summits corresponding to an elevational gradient of 2700-3300 m.a.s.l. were chosen. At each summit, the sampling of the vegetation was structured in two parts:

1. Detailed sampling in 16 permanent quadrats of 1x1 m, delimited by plots of 3x3 m laid out in the four cardinal directions. In these, the species composition and cover of each component were recorded (plants, bare soil, rock, etc.). Also, the frequency of appearance of each biotic and abiotic component considered was registered.

2. Sampling was conducted in 8 sections of the summit area. The sections were delimited by the main directions and two lines at 5 and 10 m of difference in level from the central point of the summit, situated in the highest area.

For each section, the composition in taxa and its corresponding cover were estimated according to a scale of qualitative abundance based on the representativeness (dominant, common, widespread, rare, very rare, or locally present). Also, representativeness was estimated, expressed in percentages of different types of surfaces [1].

- Thermicity index (S): Σ(elevation range) ($species_i$) x cover ($species_i$)/Σcover ($species_i$). The range is assigned with the chorology described in the standard floras. This index gives an idea of the plasticity of the species of the community to live at different elevations. High values indicate the presence of species that have broad elevational survival ranges.
- Thermophilization index: calculated as the difference between the previous one at different samplings.

› Results

The temperature difference between the summit situated at a lower elevation and the highest (549 m of difference) was 4.42ºC.
The lowest temperatures in winter and summer are located at the sites oriented towards the north and towards the west.

Richness: In total, 102 taxa were recorded, of which 34 are endemic to Sierra Nevada and another 16 are Betic endemisms. These belong to 29 botanical families, notably Asteraceae (n=17), Poaceae (n=15), Brassicaceae (n=11), Caryophyllaceae (n=10), and Lamiaceae (n=6). The proportion of endemic species rises with elevation from 23% in the lowest summits to 67% in the highest [2].

Cover: an increase was detected in the cover with respect to the year 2001. This was especially noticeable at the sites oriented towards the south, while the opposite pattern was appreciable in the localities oriented towards the east. The cover has increased at sites situated below 3000 m.a.s.l., although it has descended slightly at the higher sites (›3000 m.a.s.l.) (Figure 1).

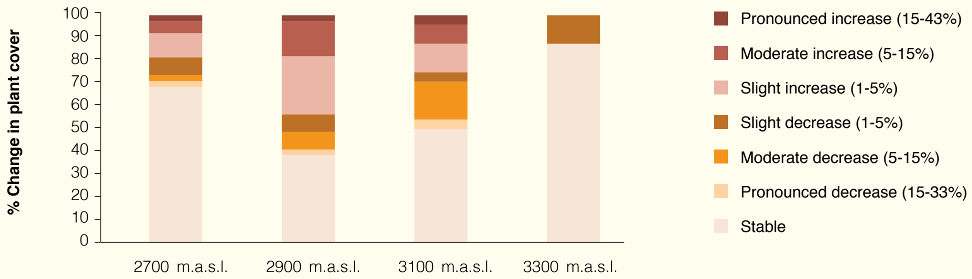
Diversity: at all the spatial scales studied (1x1 m, 3x3 m, and the scale of the summit), a negative relation was found between species richness and elevation, and a positive relation between species richness and mean soil temperature [2].

In terms of change over time, there were no major changes in the community composition at the highest elevations. However, at the lower elevations, 6 taxa were lost. For all the sites studied, 13 disappearances were recorded and 5 species that had not previously recorded were found.

Elevational migrations to the summit were recorded for some species (*Plantago radicata* subsp. *granatensis, Pilosella castellana,* and *Eryngium glaciale*). In parallel, a negative trend was appreciated in the size of the distribution area, which is especially acute in *Lepidium stylatum*, *Viola crassiuscula*, and *Saxifraga nevadensis*.

The thermophilization index (IT): the positive trend of the IT detected in the period 2001-2008 was reversed in the period 2008-2012 (Figure 2). This index provided the composition of the community in terms of diversity and coverage of plant species adapted to cooler or warmer climate conditions. The results for the period 2001-2012 show a general decline in the thermophilization of the summit areas of Sierra Nevada.

Figure 1



Changes in coverage of the plant taxa studied for the period 2001 to 2012.

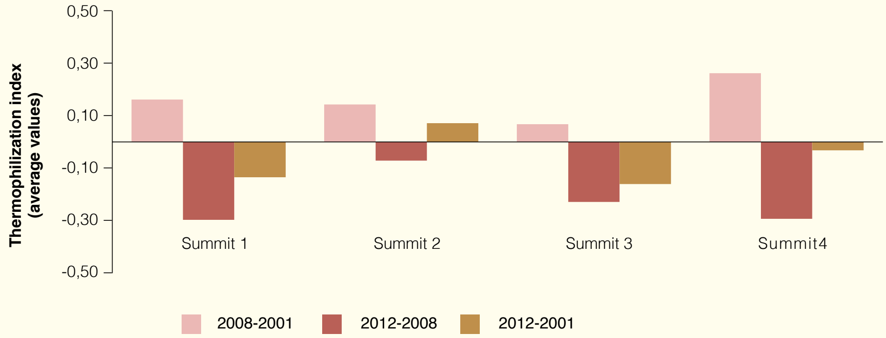
Discussion and conclusions

The last decades have been the warmest since instrumental measurements began to be recorded. This warming is causing major changes in the mountain areas of Europe, which translate in the reduction of areas with alpine conditions. The results of the GLORIA project indicate marked changes in high-mountain vegetation, implying mainly disappearances of some species and the appearance of others, elevational migrations, and changes in the plant cover [3]. At some sites studied in Sierra Nevada, 13 species have disappeared in 11 years at the same time as 5 taxa have been recorded for the first time there. Especially pronounced is the reduction in the distribution area of *Lepidium stylatum*, *Viola crassiuscula*, and *Saxifraga nevadensis*. Other species show a clear ascending trend (e.g. *Plantago radicata* subsp. *granatensis*, *Pilosella castellana*, and *Eryngium glaciale*). These changes agree with those reported at other points of Europe, where species of *Saxifraga* are also becoming rare (in Northern Europe over the last 80 years) or *Pilosella* (which has ascended in elevation in the southern Alps) [4].

At the continent scale of Europe, in the period 2001-2008, the plants best adapted to cold environments became rare, whereas those adapted to warmth prospered. Alpine plant species in 13 northern and temperate European mountain systems have moved an average of 2.7 m higher in only 7 years, and 2.5 m higher in Mediterranean mountains [3]. The ascent of the more thermophilous plants [4] has led to greater species richness in the northern and temperate summits (3.9 species on average), but in the Mediterranean mountains increases in the species at the summits have reportedly been surpassed by the loss of cryophilous species, resulting in a net loss averaging 1.4 species [3]. These observations have proved independent of elevation and latitude, as they occur both at the tree line as well as in the summits and from Scotland to Crete. However, at the scale of Sierra Nevada, this trend appears to have reversed in the period 2008-2012. The results found could be showing the adaptive capacity of certain plants under global warming.

Long-term monitoring would establish the trends in the elevational dynamics of extinction-colonization and expansion-retraction. The interpretation of the results found in Sierra Nevada in a broader geographic context is fundamental in order to establish common patterns in different high-mountains.

Figure 2



Comparison of the Thermophilization index (TI) between the monitoring periods, expressed in terms of average value by summit and time periods (years).

Festuca pseudoeskia at the site of Cúpula.

5.2. Plant population trends in Sierra Nevada

Muñoz, J.M. and Sánchez-Rojas, C.P.
Environment and Water Agency of Andalusia

Abstract

The annual monitoring of the populations of *Laserpitium longiradium* Boiss., *Arenaria nevadensis* Boiss & Reut., *Gentiana lutea L.* subsp. *lutea*, and *Senecio nevadensis* Boiss & Reut. were evaluated for their state of conservation to identify factors determining their population dynamics. The population of *L. longiradium* showed no net changes in its distribution, or abundance, nor in its population structure in the last 14 years. The distribution areas of *A. nevadensis* diminished over the time series, while its density and accompanying species slightly increased. *G. lutea* subsp. *lutea* also showed stable demographic features, fundamentally due to the longevity of the specimens. In the year following the installation of the exclusion fences, the percentage of reproductive individuals with dispersal capacity substantially increased. However, no seedlings were found to be present. Meanwhile, *S. nevadensis* increased the population abundance above 3000 m.a.s.l., but lower than this elevation the number of individuals markedly diminished.

Aims and methodology

Laserpitium longiradium: To monitor the population structure of this species, each specimen was categorized into one of these demographic stages: seedling, juvenile, vegetative adult and reproductive adult.

Arenaria nevadensis: The extent, demography, and reproductive capacity was analysed in two populations: Veta Grande (one nucleus) and Mulhacén (three nuclei). The number of individuals were counted annually by fixed transects. At each site, 30 individuals taken at random were measured for size and number of reproductive structures, as well as density, measuring the minimum inter- and intraspecific distances.

Gentiana lutea subsp. *lutea*: The life stage was recorded annually (seedling, juvenile, vegetative or reproductive), as well as the size of each individual, its reproductive capacity by the quantity of flower verticils, the number of fruits, and herbivore damage. The impact of herbivory was measured by comparing the above variables in areas protected by fences that excluded livestock with respect to adjacent areas without fencing in four types of microhabitat: meadow, meadow-spiny broom shrubland, spiny broom shrubland, and rocky areas.

Senecio nevadensis: The abundance of *S. nevadensis* was studied in plots with a circular shape 10 m in diameter, distributed over an elevational gradient of between 2775 and 3150 m.a.s.l.. The elevational range described for the species ranges from 2600 to 3300 m.a.s.l. [5].

Results

After 14 years of monitoring, the demographic structure of *L. longiradium* remained stable, although subject to slight annual fluctuations (Figure 1a and b). The vegetative specimens clearly dominated, followed by juveniles, reproductive specimens, and seedlings. The number of reproductive adults and of the seedlings 2 years later (recruitment) were correlated (ρ_2= 0.514). Also, there was a correlation between the juveniles and vegetative adults, taking into account the lag of one and two years (ρ_1=0.844, ρ_2=0.803).

A reduction in the distribution area of *A. nevadensis* was noted together with a slight increase in the density of the accompanying species (Figure 2b).

The reduction in the distribution area was clearer in the nucleus of Veta Grande, while those of Mulhacén presented greater fluctuations between years (Figure 3 a). The average number of the reproductive structures fell during the monitoring the period (Figure 3 b).

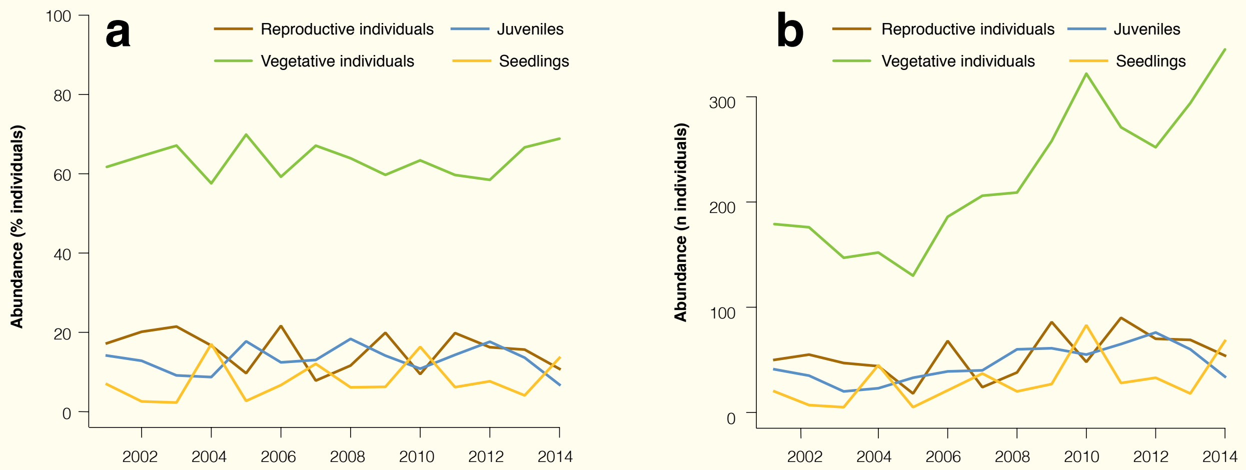
The population of *G. lutea subsp. lutea* did not vary substantially in the last 5 years. The growth rate remained stable. No seedlings were found, nor did any specimen die. The phenomenon of latency was frequent.

From the elasticity analysis [6], it was concluded that the specimens remaining in the vegetative stage, first, and those that become reproductive, second, are the transitions that most provide stability of population size (Figure 4).

The fences to exclude livestock clearly benefited the reproductive capacity of this species. The reproductive specimens inside the fenced areas (Figure 5) increased significantly ($x^2=96.95$, $p<0.001$) as well as the capacity to produce a greater number of fruits ($x^2=188$, $p<0.001$).

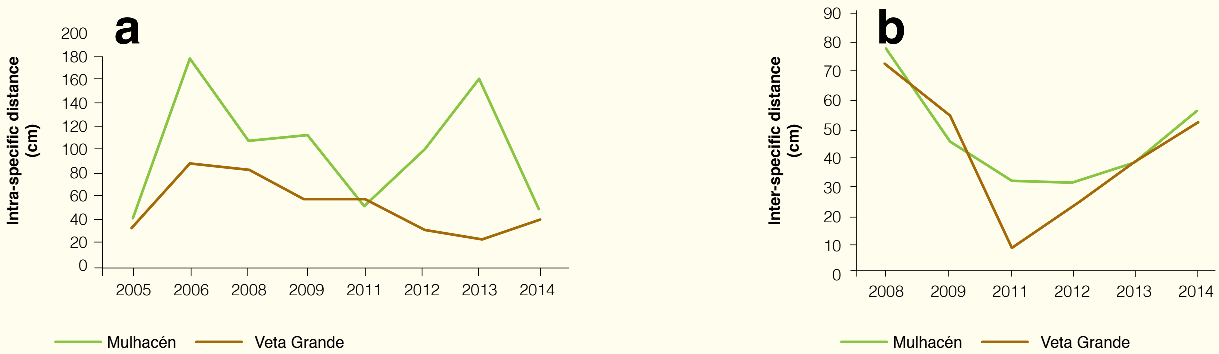
The number of *S. nevadensis* individuals remained constant, considering the total of the sites studied during the last 4 years of the monitoring. The populations situated above 3000 m.a.s.l. slightly increased in abundance, while those below presented the reverse pattern (Figure 6). In fact, at 50% of the sites studied, the abundance fell (most being below 3000 m.a.s.l.) whereas 42% augmented and 8% remained stable. The number of reproductive individuals fell considerably over the study period (Figure 7).

Figure 1



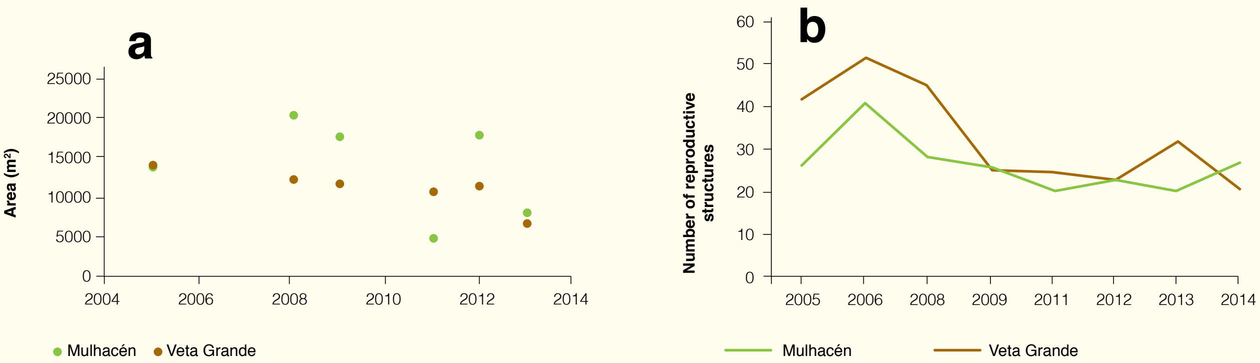
Temporal evolution (years) of each stage of population development of *L. longiradium*: a) relative values (%); b) absolute values.

Figure 2



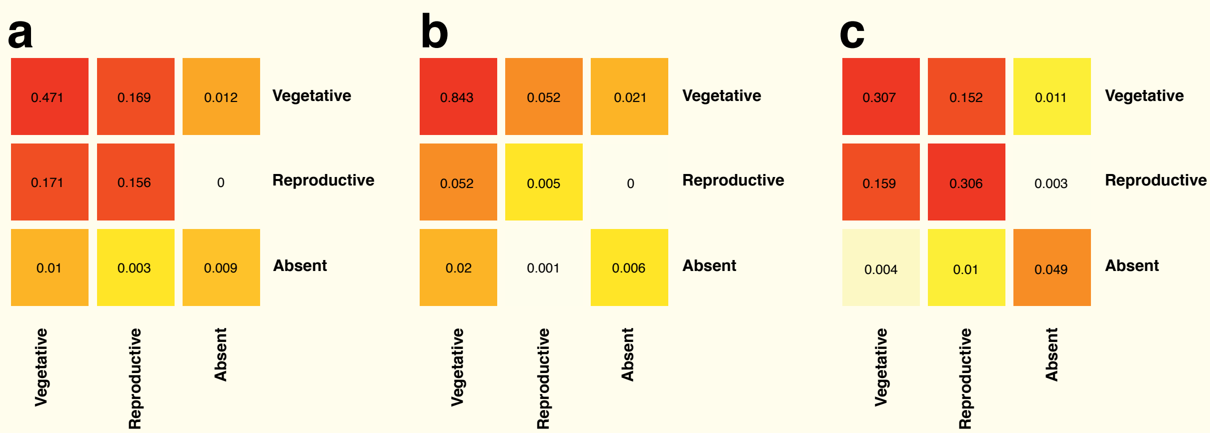
Temporal evolution of density of *A. nevadensis* individuals in comparison to other species in the habitat (expressed as the mean distance to the nearest individual in cm, n=30). Intraspecific (a) and interspecific distance (b).

Figure 3



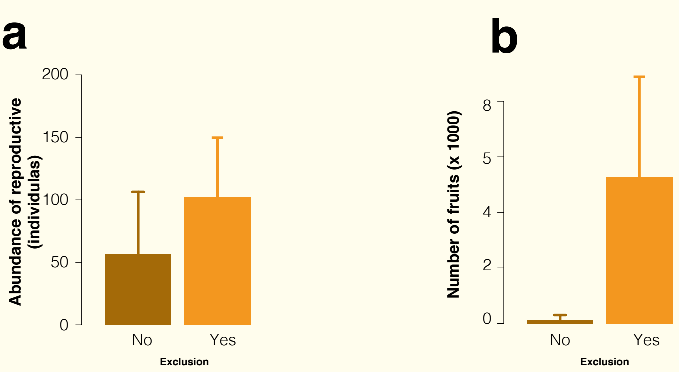
Temporal changes (years) in the distribution area (a) and in the number of reproductive structures per site (b) of *A. nevadensis* during the period 2005-2014 (n=30).

Figure 4



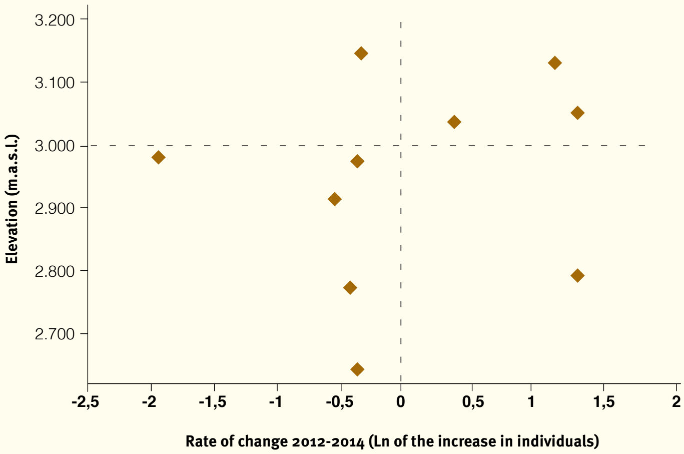
Elastiticy plots of the population of *G. lutea* subsp. *lutea*. (a) General between 2010-2014; (b) Transitions 2010 and 2011; (c) Transitions 2013 and 2014.

Figure 5



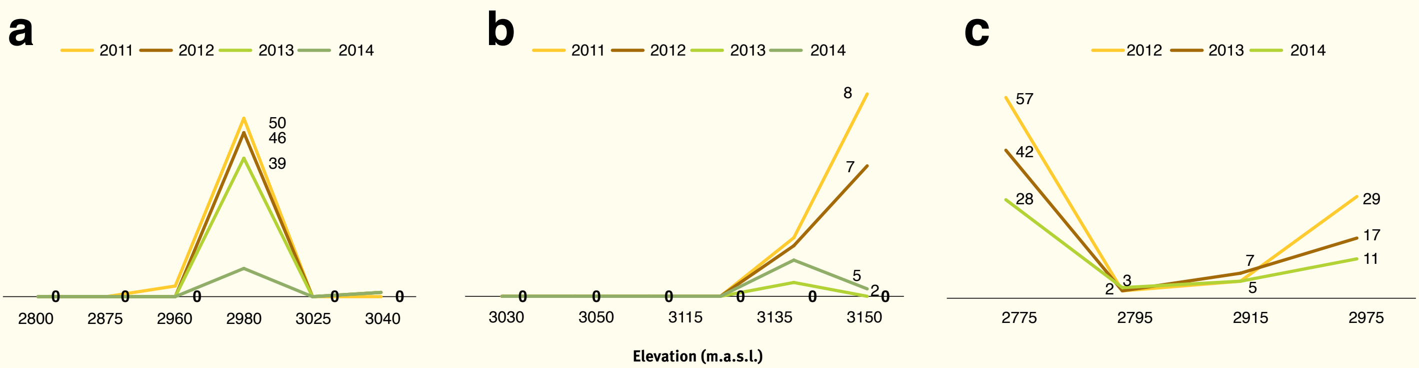
Effects of the exclusion of livestock in abundance of reproductive individuals (a) and abundance of fruits (b)

Figure 6



Changes in abundance over an elevational gradient (for the sites sampled: Veta Grande, Mulhacén, and Veleta).

Figure 7



Changes inf abundance of reproductive individulas by site (2011-2014) in absolute values: (a) Mulhacén, (b) Veleta y (c) Veta Grande.

› Discussion and conclusions

The populations of *L. longiradium* (14 years of monitoring), *A. nevadensis* (9 years of monitoring), *G. lutea* subsp. *lutea* (4 years of monitoring), and *S. nevadensis* (4 years of monitoring) presented a stable trend, over the short term. *Laserpitium longiradium* showed no changes in its population structure during the study period. Its continuity depended only on the maintenance of the characteristics of the habitat it occupied and the continuation of conservation measures begun.

Arenaria nevadensis populations remained relatively stable, given the fluctuations to be expected from an annual species of these high-mountain environments. Density was variable over the study period, especially at the Veta Grande site, but there was an appreciable trend towards an increase. The reproductive capacity (number of reproductive structures) continued to decline. Nevertheless, the continuity of this species is subjected to risks inherent in this restriction to isolated enclaves. In this sense, the results of a genetic study [7] point to a low dispersal capacity as a limiting factor for the expansion of the species and to risk of genetic depression by inbreeding, given the low genetic flow between its core populations.

The monitoring of *Gentiana lutea* subsp. *lutea*, indicated the effectiveness of the conservation works undertaken. Although highly beneficial for its reproductive capacity, the expected positive effect on recruitment was not detected. The elasticity analysis implies that the longevity of these adult specimens is a key factor in the persistence of the population. According to other studies [8], the viability of the seeds is very sensitive to population size.

The population of *Senecio nevadensis* registered positive growth rates at its upper elevational limit, above 3000 m.a.s.l.. However, this increase was not generalized at all the sites, so that other factors might be involved, such as the rocky structure, unstable soil, and herbivory. The effect of herbivores may be important, both for the browsing as well as moderate nitrification [9]. The reproductive rate diminished in the monitoring period and showed notable annual fluctuations. For its late flowering, the species is characterized by showing marked fluctuations in fruit production and seedling recruitment in relation to colder years during the critical period for reproduction [9]. This may explain the differences detected and could represent a limitation for the species conservation.

Gentiana lutea subsp. *lutea*

5.3. Amphibians and global change in Sierra Nevada

González-Miras, E.[1]; Ballesteros-Duperón, E.[1] and Benítez, M.[2]

[1] Environment and Water Agency of Andalusia [2] University of Granada

Abstract

Amphibians, for their physiological and ecological particularities, constitute one of the groups most sensitive to global change. Between the years 2009 and 2013, different aspects of their ecology related to temperature and water availability in Sierra Nevada were studied. The resulting data indicated changes in amphibian communities in Sierra Nevada, notably: a movement of amphibians in elevation, greater competition among species that reproduce in permanent water bodies, changes in size of the metamorphic stages, and the expansion of emerging diseases.

Aims and methodology

A literature review of the distribution of the amphibians in Sierra Nevada was carried out. All references were grouped into two periods: old citations (prior to 2005) and current ones (after 2008). The elevational distribution was compared for different species detected in the two periods considered.

Also, the breeding dates of three amphibians were studied in 60 bodies of water distributed throughout the elevational gradient. Of the species studied, two reproduced in permanent water bodies (betic midwife toad *Alytes dickhilleni* and common toad *Bufo spinosus*) and another in temporary bodies of water (natterjack toad *Bufo calamita*).

The metamorphic individuals of the Betic midwife toad were weighed and measured along an elevational gradient. Also, the water temperature was continuously measured using data loggers at 13 reproduction sites distributed throughout the gradient. The data were collected from June to October, at regular intervals of 30 min and compared with the optimal growth temperature in order to establish the margin of thermal safety and warming tolerance.

Also, 15 temporary ponds situated along 3 elevational gradients were monitored. The hydroperiod length and the reproduction success for each species were recorded. In the case of the Betic midwife toad, the success in metamorphosis was registered in 18 areas subjected to different degrees of management, with the aim of creating an early-alert network for chytridiomycosis. Finally, for this species, 40-50% of the larvae were marked in 5 streams (with elastomeres visible). These were marked with different colours to determine the movements between ponds.

Results

In the last 30 years, 5 species have ascended elevationally. This trend was significant for the common frog *Pelophylax perezi*, for the common toad, and for the spanish painted frog *Discoglossus galganoi jeanneae* (Table 1 and Figure 1).

The Betic midwife toad and the common toad showed a clear phenological lag as they ascended in elevation (Figure 2), this being clearly related to temperature. These 2 species, which often reproduce in the same places, are currently phenologically uncoupled, possibly reducing interspecific competition [10].

The larvae of most betic midwife toad populations tolerate low water temperatures in relation to their physiological optimum, this being especially evident in the case of those that reproduce in streams. The artificial media studied present a more appropriate temperature for the development of amphibians. Although the development in cold places was slower, the size and final weight of the metamorphic forms was greater (Figure 3).

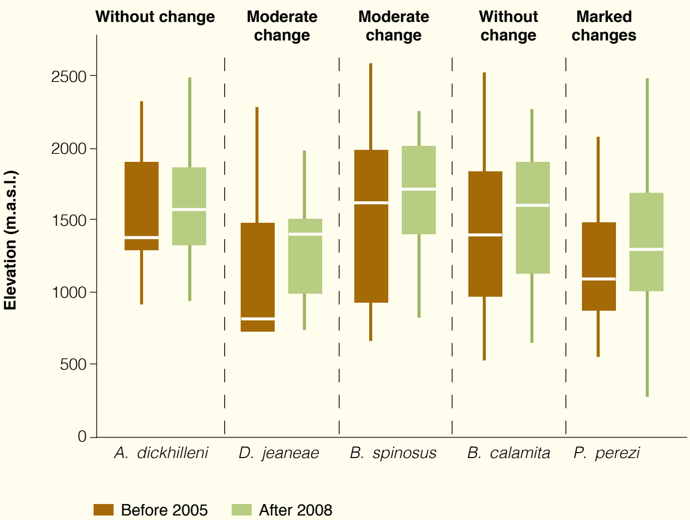
To date, no case of chytridiomycosis has been detected in Sierra Nevada. However growing prevalence of this disease at nearby sites and the conditions of Sierra Nevada suggest a high risk of this pathology appearing.

Table 1

Species	Water bodies	Number of records before 2005	Number of records after 2008	Mean elevation before 2005	Sd	Mean elevation after 2008	Sd	W	t	g.l.	P
A. dickhilleni	Permanent	18	32	1,548.72	413.83	1,629.03	416.82		0.74	17	0.47
B. spinosus	Permanent	62	80	1,519.39	605.18	1,692.20	376.49		2.11	61	0.03*
B. calamita	Temporary	23	26	1,445.65	556.15	1,497.38	501.66		1.21	22	0.24
P. perezi	Permanent	85	130	1,215.36	426.90	1,306.63	487.47		9.23	84	0.00**
D. galganoi jeanneae	Temporary	22	8	1,180.27	539.27	1,322.12	422.38	28	-----	-----	0.02*
P. ibericus	Temporary	2	-	1,482.00		------			-----	-----	-----
H. meridionalis	Temporary	7	-	764,.00		------			-----	-----	-----

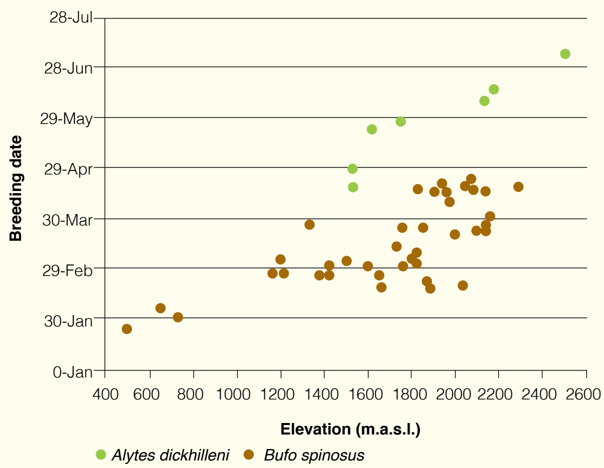
Number of citations and mean elevation of the amphibians found prior to 2005 and after 2008, and the results of the parametric Student's t-test for species with a distribution of citations fit to normality (Shapiro-Wilk test), except for *D. jeanneae*, for which the non-parametric *Wilcoxon-Mann-Whitney* test was applied. Asterisks indicate species with significant differences.

Figure 1



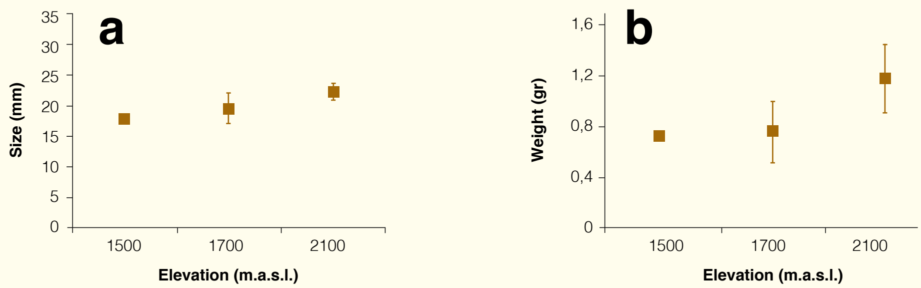
Comparison by box diagrams of the mean elevational distribution of the previous citations before 2005 and after 2008 of 5 species of amphibians in Sierra Nevada.

Figure 2



Breeding date in relation to elevation for the Betic midwife toad and common toad.

Figure 3



Size and mean weight of the metamorphic forms of the Betic midwife toad. With ascending elevation, the size and weight of the metamorphic forms are larger, both variables being significant. Kruskal-Wallis Test for size ($X^2=7.092$; g.l.=2; $p<0.05$) and weight ($X^2=7.409$; g.l.=2; $p< 0.05$).

Discussion and conclusions

The results show that the amphibians in Sierra Nevada have ascended in elevation a mean of 107.8 m in the period 2008-2011 in relation to the period 1980-2005. From the 7 species studied, 3 showed a clear ascending pattern (the Iberian painted frog, common toad, and common frog), 2 showed no definite pattern (Betic midwife toad, and natterjack toad), and another 2 tended to become rare and disappear (*Hyla meridionalis* the mediterranean tree frog and *Pelodytes ibericus* the iberian parsley frog).

Forecasts for temperature rises imply major changes in the amphibian communities of Sierra Nevada. The main changes for the amphibians are diagrammed in Figure 4.

In general, high-mountain populations may benefit from a temperature rise, while those of the low and middle mountains face a serious risk of disappearing, especially those of temporary media [11]. In high-mountain populations, an increase in water temperature would involve early physiological development and a reduction in the larval period, which would spur the rate of population growth and reduce the risk of contracting chytridiomycosis. At sites located in streams, the frequency of overflows and other extreme phenomena is expected to grow in frequency. Furthermore, the changes predicted in phenology of breeding date due to climate change may spur changes in the assemblages of amphibian communities.

The populations in low and medium mountains are currently closer to optimal physiological conditions, but they risk undergoing greater physiological stress and disappearance in the event of excessive increases in water temperature. In this scenario, a decline would occur in the quantity of dissolved oxygen in the water, which may hamper the development of embryos and larvae.

With regard to temporary *vs*. permanent media, species that reproduce in temporary media are in clear decline. Despite that the sampling effort after 2008 was greater than before 2005, the number of records of this species was lower, and some had even apparently disappeared from the Sierra Nevada Protected Areas (iberian parsley frog and the Mediterranean tree frog). In fact, the data available indicate that temporary ponds are the water bodies in the poorest state of conservation, although they have the highest diversity. Many of them have sharply reduced water periods, a situation that may be aggravated by global warming [12].

The Iberian painted frog is one of the species that has undergone an elevational ascent of the greatest magnitude in Sierra Nevada.

Figure 4

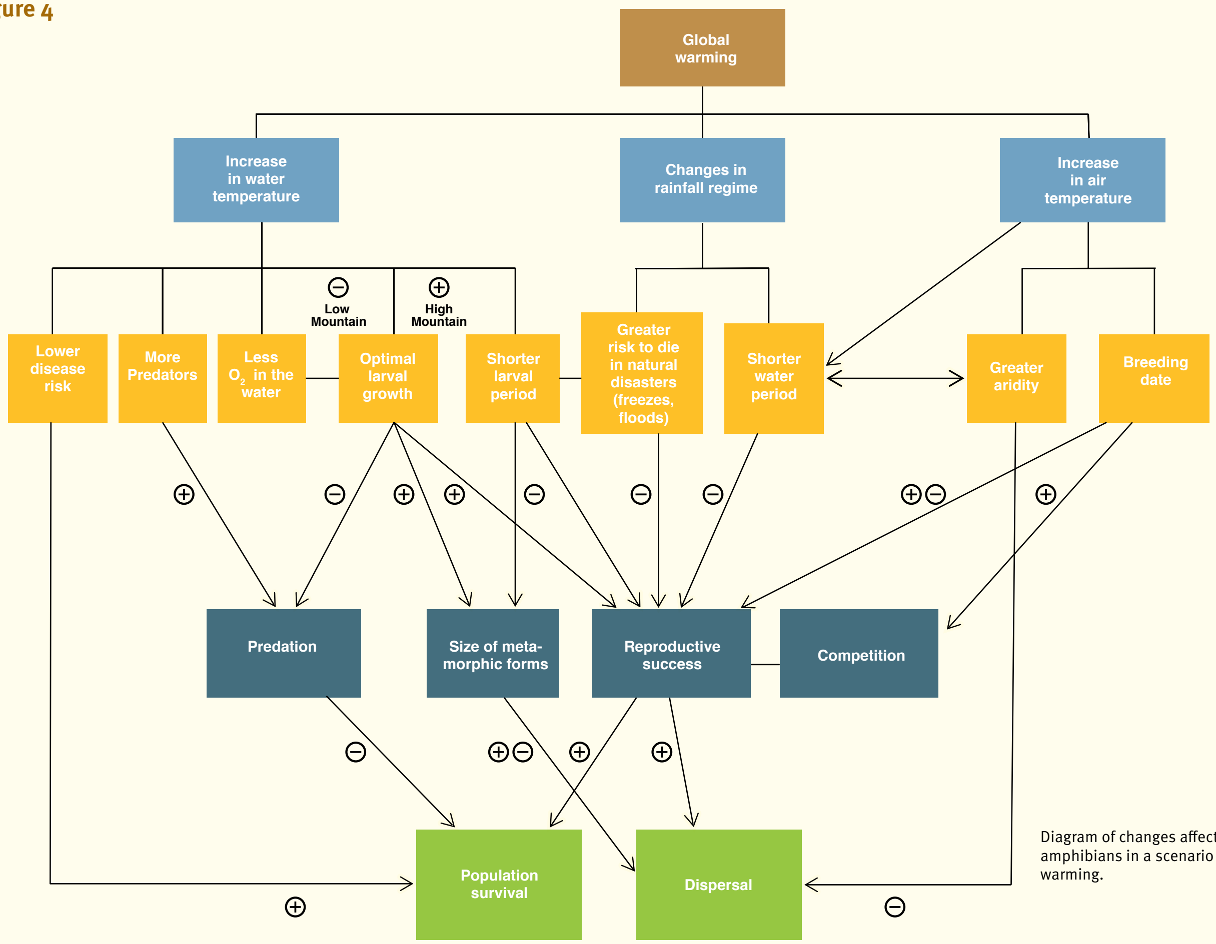


Diagram of changes affecting amphibians in a scenario of global warming.

Temporary ponds and species that reproduce in them, such as the Iberian painted frog, are strongly affected by climate warming in Sierra Nevada.

5.4. Changes in the bird communities of Sierra Nevada

Zamora ,R.[1] and Barea-Azcón, J.M.[2]

[1] Andalusian Institute for Earth System Research. University of Granada [2] Environment and Water Agency of Andalusia

Abstract

The changes in the composition and abundance of passerine communities were studied along an elevational gradient, comparing the results found by censuses made in three different habitats (oak forest, high-mountain juniper scrublands, and high-mountain summits) at the beginning of the 1980s and at present. The results indicate that in the last 30 years, notable changes have taken place in the composition and, especially, in the abundance of the passerine communities. Significant declines in populations were appreciated in many of the species that were dominant in the 1980s, particularly in oak forests and in high-mountain juniper scrublands. The magnitude of the changes diminishes with elevation, and therefore the ecosystem that has changed the most was the oak woodland and those that changed the least were the ecosystems of the high-summits. The bird communities in Sierra Nevada showed a strong spatio-temporal dynamic that appears to be accentuated by global change.

› Aims and methodology

The censuses of reproductive birds compiled at the beginning of the 1980s and at present (2008-2012) were compared. The sites studied were the same in both periods: an oak forest located at 1700 m.a.s.l., an area of high-mountain juniper scrubland at 2200 m.a.s.l. and the high-summit area, at around 3100 m.a.s.l.. The censuses were made along linear transects with a fixed bandwidth of 50 m, 25 m on each side of the observer. The sampling effort was similar in both periods. The historical data were compiled by R. Zamora over the first half of the 1980s (oak forests, 1981; high-mountain shrublands 1982, 1985, and 1986; and high-summits 1982) [13 - 17]. The current censuses were undertaken within the framework of the Sierra Nevada Global Change Observatory from 2008 to 2012, during the reproductive period.

› Results

a) Oak forests (1700 m.a.s.l.):

In 1981, 21 species were recorded, while the mean number of species/year recorded in the current period was 18.8±3.7. In the period 2008-2012, a total of 31 species were registered. Out of these, 6 species had not been recorded in 1981: the long-tailed tit (*Aegithalos caudatos*), European crested tit (*Lophophanes cristatus*), black redstart (*Phoenicurus ochuros*), common firecrest (*Regulus ignicapillus*), Eurasian nuthatch (*Sitta europea*), and the subalpine warbler (*Sylvia cantillans*). On the other hand, 3 species, despite being located frequently in 1981, currently have not been cited in any of the censuses: European goldfinch (*Carduelis carduelis*), Eurasian golden oriole (*Oriolus oriolus*), and European green woodpecker (*Picus viridis*). Consequently, the turnover rate is 37.9 %.

In oak forest the bird density in 1981 was 108.1 birds/10 ha, whereas in the current period was 37.5 birds/10 ha. This was due primarily to the regression of dominant species in 1981, especially the Eurasian blue tit (*Cyanistes caeruleus*), the Western Bonelli's warbler (*Phyloscopus Bonelli*), Eurasian jay (*Garrulus glandarius*), and common blackbird (*Turdus merula*).

b) High-mountain shrubland (2200 m.a.s.l.):

No major changes were detected in diversity (1982, 1984 and 1985: 9.7±1.5 species/year and 2008-2012: 9.4±1.1 species/year). In total, 9 species common to both periods were detected, with a community turnover rate of 29,1 %. One of the most notable changes was the appearance of the European stonechat (*Saxicola rubicola*), which was not detected in the 1980s but is currently a common bird. Also striking was the replacement of the common whitethroat (*Sylvia communis*) by the spectacled warbler (*Sylvia conspicillata*). Species such as the woodlark (*Lullula arborea*), the Thekla lark (*Galerida* *thecklae*) or dunnock (*Prunella modularis*) were detected in current censuses but not 30 years ago. The density of bird populations declined from 30.2 birds/10 ha in the 1980s to 10.5 /10 ha at present. The abundance of a key species of these ecosystems such as the wheatear (*Oenanthe oenanthe*) drastically descended from 10.1 birds/10 ha in the 1980s to 2.3 birds/10 ha at present.

c) High summits (3100 m.a.s.l.):

These ecosystems, characterized by a restricted phenological window and a low bird diversity have undergone a certain net gain in species during the last three decades. In 1982, 3 species were located while currently the total number is 5 (4±0.8 species/year). The turnover rate in this period was 13.4 % and, in contrast to the other two locations studied, the density increased from 4 to 4.9 birds/10 ha. The common linnet (*Carduelis cannabina*) appeared to be reproductive, while the black redstart increased in the summit ecosystems of Sierra Nevada. The Alpine accentor became rare during this 30-year period.

Discussion and conclusions

The two main drivers of global change in Sierra Nevada are climate change and the land-use changes. The climate change for the study period (1981-1986 *vs*. 2008-2012) consisted of a rise in the temperature of 0.105°C annual (see Chapter 1). The precipitation patterns, on the other hand, are irregular and follow a non-consistent trend. In the low and medium areas, changes in land-use in the last few decades have led to the expansion and densification of forests and shrublands. Overall, these changes in climate and in land use alone do not appear to explain the substantial alterations in the bird communities over the last 30 years. Despite that the diversity values have not greatly changed, a decline has been confirmed in the density of the species that were dominant in the 1980s, such as the wheatear in the juniper high-mountain shrublands, or the Eurasian blue tit in the oak forests. A high rate of turnover has been found in the species composition of the community (26.8 % on average). These results suggest that this uncoupling between environmental changes and changes in the communities are related to

Figure 1

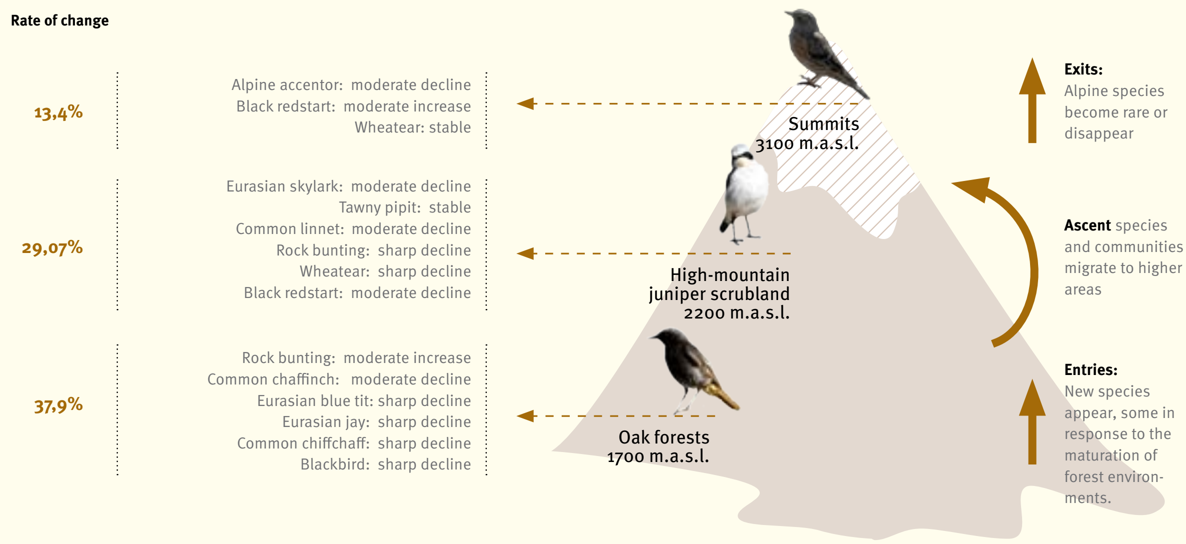
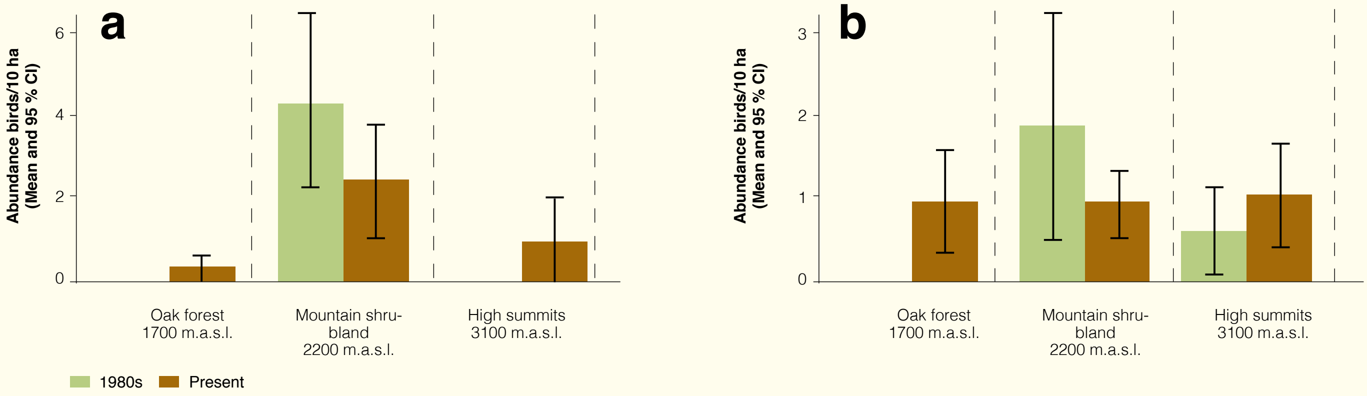


Diagram summarizing the changes found in the high-mountain bird community over the last 30 years over a gradient of elevations and habitats.

the unsaturated character of mountain communities, exposed to constant entries and exits of species. Gradually, the high-mountain bird community of Sierra Nevada is losing its Alpine character and becoming homogenised with the Mediterranean conditions of its surroundings. The clearest example at present is the Alpine accentor, but hints of this process are also found in the disappearance of other Alpine species that were seen by the first naturalists who visited Sierra Nevada in the 19th century, such as the wallcreeper (*Trychodroma muraria*), the white-winged snowfinch (*Montifringilla nivalis*) or the Alpine chough (*Pyrrhocorax graculus*).

On the contrary, current conditions also offer opportunities for generalist species, such as the black redstart or the common linnet to colonize the high mountain.

Figure 2



Changes in the distribution and abundance of the linnet (a) and black redstart (b) along the altitudinal gradient of Sierra Nevada.

The Alpine accentor (*Prunella collaris*) is the species of nesting bird in Sierra Nevada that is most associated with the Alpine conditions still persisting in the summits of this mountain.

5.5. Temporal dynamics of cliff-nesting raptor populations in Sierra Nevada

Martín, J.[1]; Barea-Azcón, J.M.[1]; López-Sanjuan, R.[1] and Gil-Sánchez, J.M.[2]

[1] Environment and Water Agency of Andalusia [2] Wilder SOUTH Society

Abstract

The temporal dynamics of the golden eagle and peregrine falcon populations in Sierra Nevada were analysed for the last 7 breeding seasons and for Bonelli's eagle during the last 12 seasons. The 23 pair of golden eagles of this subpopulation make it one of the largest of the south-eastern Iberian Peninsula. Most of the breeding pairs are distributed on the long axis of the mountain range as well as at the middle and high areas of the large fluvial and glacial valleys. The 15 pairs of Bonelli's eagles occupy areas with the greatest thermicity of the mountain range, coinciding with the carbonate zone. Its trend over the last 10 years is also stable, although its productivity continues to fluctuate, probably depending on climatic parameters. The peregrine falcon population of Sierra Nevada remains stable, with a slight increase to 14 breeding pairs.

Aims and methodology

The trends in the populations of the golden eagle (2008-2014), Bonelli's eagle (2003-2014), and peregrine falcon (2008-2014) were analysed in Sierra Nevada from two reproductive parameters of reference (productivity and number of territories occupied). After the identification of breeding pairs, the reproductive process was monitored based on at least 3 visits per pair during which incubation, number of hatchlings and number of fledglings that finally left the nest were verified. Productivity was calculated as the total number of fledglings that left the nest/occupied territory. A territory was considered occupied on confirming an incubation, chicks in the nest, or the consistent presence of individuals in the territory over different visits. To analyse the effects of climatology on the productivity, a multiple regression was made where the dependent variable was productivity of each of the species, and the independent variables were monthly temperature and accumulated precipitation at 6 weather stations representative of the study area situated from 600 to 2150 m.a.s.l. (mean 1445.83 m.a.s.l.). Monthly temperature and precipitation were included for January and May, the average for these 5 months, and the average for the first 3 months as a reference for the conditions in the preliminary phases of the reproductive period.

Results

In Sierra Nevada, the presence of 23 golden eagle territories were confirmed in 2014 as opposed to 19 in 2008, at the beginning of the monitoring programme. This value represents a density of 1.34 territories/100 km², which is greater than the density reported for the provinces of Granada (0.46/100 km²) or Almería (0.39/100 km²), and is similar to that established for other mountains of the Betic range. The productivity trend fluctuated over the last 7 years, with peaks alternating with troughs in successive years (Figure 1). The mean value for this parameter during the period 2008-2014 was 0.8 fledglings/territory occupied, which is under the Andalusian mean for the year 2008 (1.04 fledglings/territory occupied) and is identical to the Spanish mean for this same year (0.8 fledglings/territory occupied) [18].

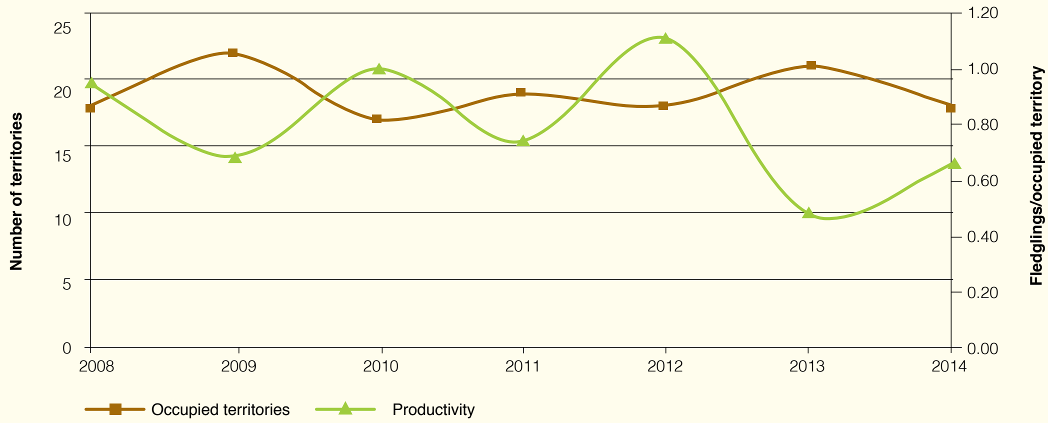
Bonelli's eagle presented 15 territories in Sierra Nevada. Population trend since 2003 appears to be a slight increase for a gain of 5 territories, although since 2013 two of those territories has been lost. Density of this species in Sierra Nevada is 0.93 territories/100 km², while for the rest of Andalusia the rate is 0.37 territories/100 km² and in Spain the figure is 0.15 territories/100 km². As in the case of the golden eagle, the density of territories is similar to that of other mountain areas of the Betic range. Productivity shows a slightly negative trend since, in 2010 and 2013, only 7 fledglings to leave the nest in a total of 10 territories occupied,

while in 2014 only 9 fledglings left the nest in 9 territories occupied (Figure 2). This plunge in productivity was also registered in the rest of the province of Granada (Gil-Sánchez, unpubl. data). Even so, the mean value for the period 2003-2014 was 1.23 fledglings/territory occupied, which is higher than the Andalusian mean for the year 2005 (1.17 fledglings/territory monitored) and far higher than the Spanish mean for this same year (0.92 fledglings/territory monitored)[19].
Ever since the monitoring program was started (2008) the population of peregrine falcon has increased from 11 to 14 territories, although it is highly probable that the increase is not real but due to improved sampling coverage. This implies a density of 0.81 territories/100 km². This value is far higher than the density for Andalusia in the year 2008 and also greater than for Spain in the same year (0.32 and 0.49 territories/100 km², respectively). The productivity of the peregrine falcon population of Sierra Nevada for the period 2008-2014 was 1.51 fledglings/territory monitored (Figure 3). This value can be considered moderate or even low, taking into account that the mean productivity in Andalusia and Spain in general are 1.74 and 1.42, respectively, for 2008 [20].

Influence of climate on cliff-nesting raptor reproduction in Sierra Nevada

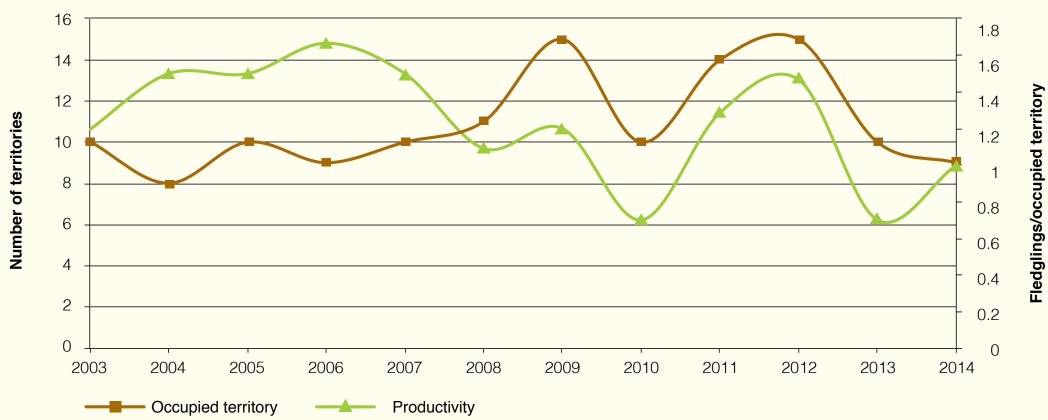
Only the productivity of Bonelli's eagle proved to be influenced by climatic variables considered in the analysis ($p<0.05$). In this way, the multivariate analyses showed that the abundance of the precipitation during the month of March was negatively correlated with productivity in this species (Figure 4).

Figure 1



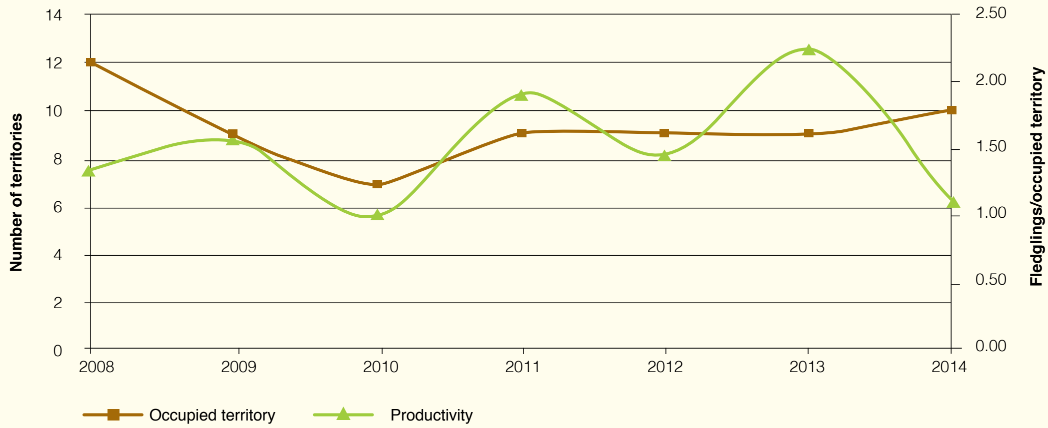
Productivity and number of occupied territories by the golden eagle in Sierra Nevada. Annual values since 2008.

Figure 2



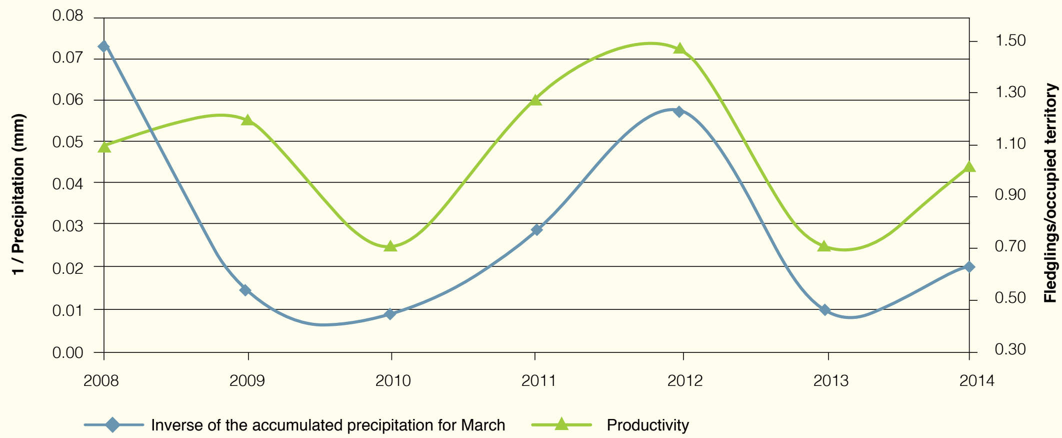
Productivity and number of occupied territory by Bonelli's eagle in Sierra Nevada. Annual values since 2008.

Figure 3



Productivity and number of occupied territory by peregrine falcon in Sierra Nevada. Annual values since 2008

Figure 4



Relation between productivity of Bonelli's eagle and accumulated precipitation during the month of March.

› Discussion and conclusions

The golden eagle population, with 23 territories, is one of the most important of the Betic ranges. The trend of the population in recent years should be considered stable, as the slight increase detected may be due to the better sampling coverage. The productivity of the population during the last 7 years presents a fluctuating trend inversely related to the number of territories occupied (r_s= 0.71; g.l.= 6; p‹ 0.05). This is because the number of chicks is usually lower in the breeding seasons in which the number of occupied territories is higher, though this relation does not reach statistical significance (r_s= 0.49; g.l.= 6; n.s.). An increase in the population size and greater proximity to the closest territory of the same species negatively influences productivity.

Bonelli's eagle population has grown slightly since 2003 in contrast to a clear surge of the species in the rest of Andalusia. In Sierra Nevada, the golden eagle colonizes the long axis of the mountain range as well as the middle and high zones of the large river and glacial valleys. Bonelli's eagle is restricted to warmer and more anthropized settings, which coincide with the peripheral areas and in large part with the carbonate portion. Contrary to what occurs in the case of the golden eagle, there was a positive relation between the number of territories occupied and the number of hatchlings (r_s= 0.95; g.l.= 6; p< 0.001) during the reproduction season of 2008 to 2014. No relation was found between the two parameters in the reproduction season of 2003 to 2007. The multivariate analyses between accumulated precipitation and Bonelli's eagle population in Sierra Nevada showed a close relationship between the reduction in precipitation during March and higher values of productivity of this species. Consequently, the predictions of reduced precipitation could benefit this species [21]. In any case, the final result is hardly predictable due to the existence of phenomena of interspecific competition with the golden eagle, the repercussion of which could be considerable on the trend of Bonelli's eagle at the local scale [22].

A pair of golden eagles photographed at one of the few territories located over limestone substrates present in Sierra Nevada.

5.6. Demography of wild ungulate populations and disease prevalence

Granados, J.E.[1] and Cano-Manuel, F.J.[2]

[1]Environment and Water Agency of Andalusia [2]Andalusian Regional Ministry of Environment and Spatial Planning

Abstract

Population trends of ibex and wild boar in Sierra Nevada are presented. In the case of the Spanish ibex, the monitoring began in 1960, while for the wild boar, in 2002. The ibex in Sierra Nevada maintains the most numerous population and with the greatest genetic variability in the Iberian Peninsula. The population trend is positive, although for the last 20 years growth has slowed down. The wild boar presents stable populations as a result of population control, scarcity of food and probably reproductive diseases. Also, results related to the time course of infectious and parasitic diseases are examined in populations of ibex and wild boar. These results are of great interest, as wildlife are considered the main reservoir of more than 70% of all emerging diseases.

Aims and methodology

The Spanish ibex and wild boar populations in Sierra Nevada have been monitored, and different pathogenic agents have been studied in both species. The density of the ibex population was estimated using linear transects. The census itineraries were based on the distribution of individuals sighted along the paths taken at random in the study area. The abundance estimate was based on a model related to density parameters to be calculated. The observer, on detecting an animal, assumes that the probability of detection is a function of distance between them. Any continuous variable randomly distributed, such as the detection distance, is defined by a probability function [*f (x)*]. Sarcoptic mange was monitored by direct examination, calculating the proportion of diseased and healthy animals. Due to the ecological singularities of the wild boar and the extensive and continuous plant structure of the refuge area, the battue method was used for estimating the population structure and density of this species in Sierra Nevada. The health status of the population was determined by epidemiological monitoring of different relevant pathological agents through serological tests and various epidemiological indices.

Results

Spanish ibex

Population trend of the Spanish ibex in Sierra Nevada

Sierra Nevada harbours the most numerous population of Spanish ibex with the greatest genetic variability of the Iberian Peninsula. This population has grown in the last 40 years, from a density estimated in 1960 of 1.29 ind/km^2 to some 11.68 ind/km^2 estimated in 2012. Considering the results obtained during the demographic monitoring for the past 20 years, the population can be considered somewhat stable with a slight increase.

The genetic structure of the population

In Sierra Nevada, 4 of the 6 alleles known for the MHC (major histocompatibility complex) has been described. It is well known that high levels of polymorphism can be related to greater defence capacity against pathogens, while populations that show a markedly homogeneous genetic composition may be more susceptible to parasitic diseases.

Sarcoptic mange

Evidence exists (historical texts, experimental infection and monitoring) that indicates the existence of individuals resistant to mange in the ibex population in Sierra Nevada. The capture and marking of different specimens affected by the disease has shown that the mean survival in Sierra Nevada exceeds 209 days, which is far greater than the 90 days estimated for this species in the Natural Park of Cazorla, Segura, and Las Villas [23].

__Wild boar__

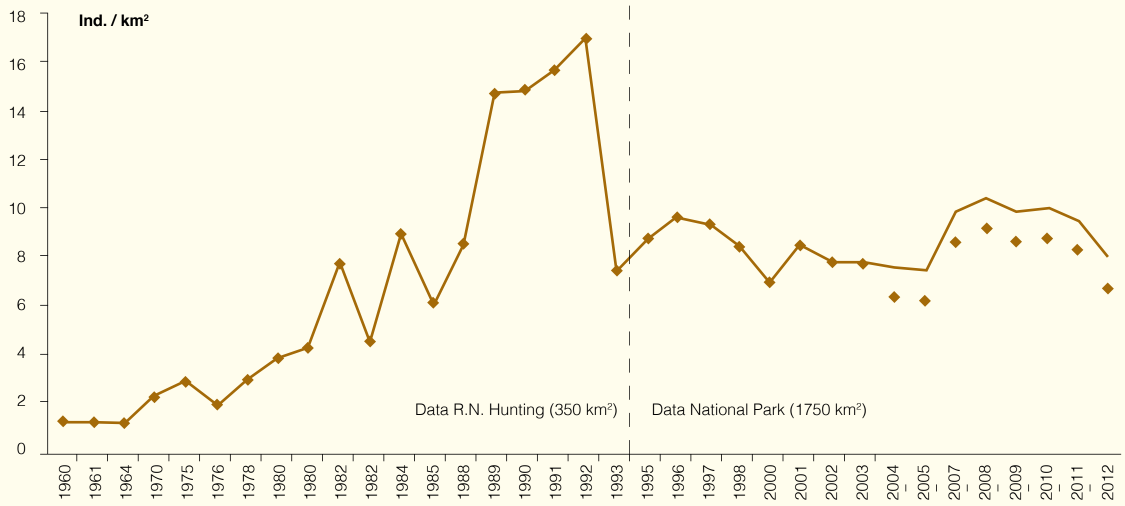
__Population trend of wild boar in Sierra Nevada__

The presence of wild boar in Sierra Nevada is very recent, dating to no earlier than 1975. From recolonizations, the expansion was rapid, taking advantage of the enormous forested area. The mean annual density estimated in the refuge area (forested area and dense shrublands) is 8.5 ind./km², and for the entire protected natural area, 2.6 ind./km² [24]. These results indicate a population decline after the implementation of a management plan and subsequent stability that continues at present.

__Health state of the population__

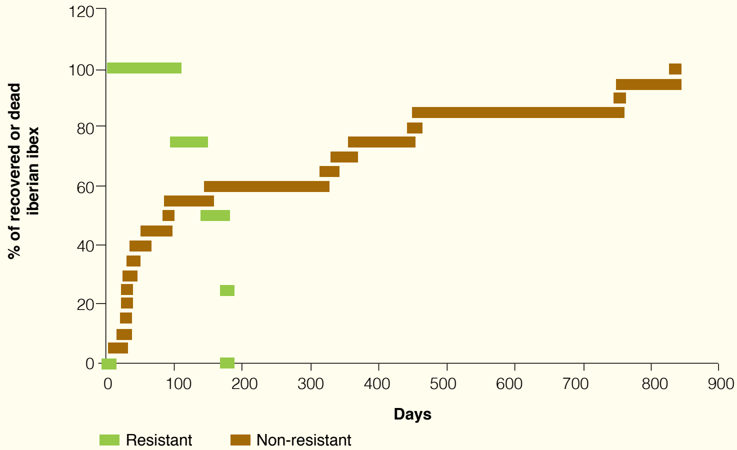
The wild boar population in Sierra Nevada has a moderate and even low infection load in general. It was confirmed, however, that the low rates of pathogen circulation detected are sufficient for the existence of continuous active foci of infections in time and space [25].

Figure 1



Evolution of the Spanish ibex population in Sierra Nevada since 1960.

Figure 2



Survival rate of animals resistant and non-resistant to mange in the Spanish ibex population in Sierra Nevada.

Female ibex with kid.

› Discussion and conclusions

Spanish ibex

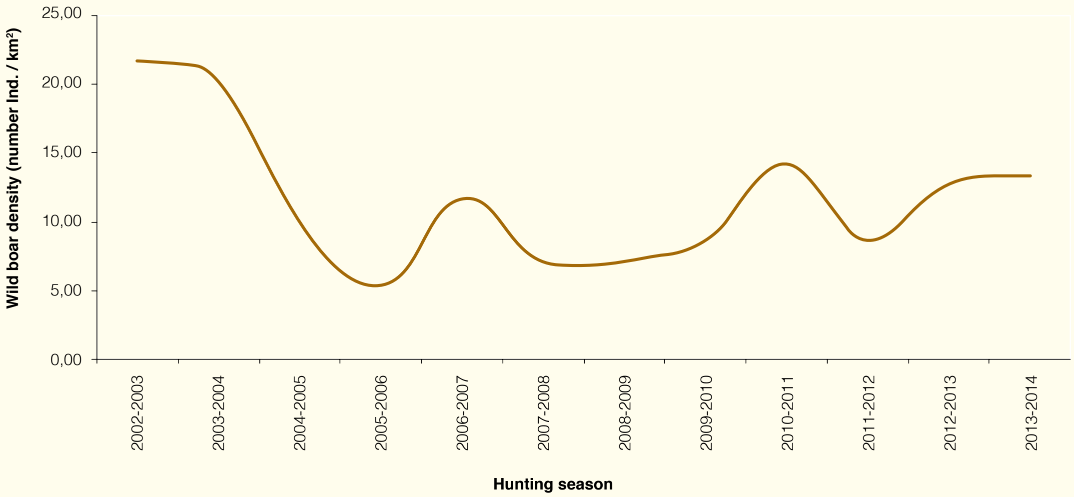
The trends of the Spanish ibex population in Sierra Nevada appear to be related to land-use changes and human depopulation. The climatic factors are not clearly involved in the results. The forecasts of global warming and the irregularity of the precipitation do not, either, signify a negative prediction for the population size, which will foreseeably continue to expand numerically, facilitating the connectivity between populations. Under these conditions, diseases (parasitic mainly) could increase in incidence, affecting the size and structure of the populations of these mountain ungulates. For example, in the Sierra Nevada population, prevalence of mange has been related to climate. Certain diseases are climate sensitive, influencing the frequency, distribution, and transmission vectors (fleas, ticks, mosquitoes, etc.). This can have an impact not only on human health but also on livestock and wildlife, particularly any threatened species, which can be pushed to extinction by stochastic events. Wild fauna is considered the main reservoir of more than 70% of all emerging diseases. The interaction of these variables in a certain time and place could lead to the establishment of epidemiological scenarios propitious for the emergence and re-emergence of vectorial infectious and zoonotic diseases. These risks should be better known and they require new mechanisms of vigilance and prevention. For this, the Spanish ibex population is being intensely monitored, not only at the population level but also with respect to diseases that affect them, integrating the epidemiological vigilance with ecological, demographic, and reproductive aspects.

Wild boar

The low productivity of the population appears to be related to food scarcity or to reproductive diseases. In species such as wild boar, which shows great populational fluctuations according to available food, management measures based on mean calculations or estimations prove less effective. The pressure exerted in the population controls and the low growth rate are considered sufficient elements to maintain admissible populational densities from the socioeconomic and environmental standpoint.

The heterogeneous distribution in space and time of the pathogens is probably determined by several factors that interact, such as the local density of the population, the behaviour of the species, the mode of transmission of each pathogen, population management, and environmental aspects including climatology. The natural reservoirs maintain pathogens in restricted geographic areas due to the characteristics of the ecosystems [26], the Marquesado and Alpujarra Alta (Granada province) having the highest concentrations of wild boar pathogens in Sierra Nevada.

Figure 3



Evolution of the wild boar population in Sierra Nevada over the last decade

Male Spanish ibex with a GPS-GSM collar.

5.7. Shifts in the elevational ranges of insects in Sierra Nevada: evidence of climate change

González-Megías, A.[1]; Menéndez, R.[2] and Tinaut, A.[1]

[1]University of Granada [2]Lancaster University

Abstract

Climate change can cause massive disruptions in biological systems due to, among other things, changes in distribution ranges of the species, phenology, and interactions with other species. Mountain areas are excellent scenarios to detect these changes because they encompass both upper and lower limits of species distribution. The present study provides evidence for distribution changes of three different groups of insects: Coleoptera, Lepidoptera and Hymenoptera. For the sampled species, it appears that in the last two decades, there has been an elevational shift in the distribution of species, with upper and lower elevational limits moving upwards.

› Aims and methodology

1. Coleoptera

To assess distributional shifts of Coleopteran species over time we selected dung beetles (Scarabaeoidea) as they are a group of species with a broad distribution in Sierra Nevada. To do that, we compared past species distributions (1981/1982) with those recorded during a more recent study (2006/2007). In both periods, dung beetles were sampled at 100 m intervals along an elevational gradient in a total of 18 sites. Climatic condition were also recorded for each time period in order to assess whether the changes detected in the species distribution were related to the differences in the climate between the two periods. Changes in mean elevation as well as changes in the upper and lower elevational limits were calculated for each species (see [27] for more details).

2. Lepidoptera and Hymenoptera

For butterflies, we assessed changes in the upper elevational limit of *Parnassius apollo nevadensis* by comparing observational data obtained by the author (AT) during the 1970s and data from the literature with current data.

For Hymenoptera, information about the distribution of two ant species (*Proformica longiseta* and *Formica fusca/lemani*) is provided. The taxonomical status of *Formica fusca* and *F. lemani* is still unresolved so data from the two species are presented together [28]. Historical distribution data are obtained from one publication [29] and a doctoral thesis [30]. The current distribution data come from surveys carry out in 2007 in several localities previously surveyed during the doctoral thesis [30]. Other current data are obtained from occasional surveys at the highest elevations in Sierra Nevada during the last 10 year and until 2013 (Table 1).

Table 1

Locality	Elevation (m.a.s.l.)	Aspect	1979-1981	2007-2013	Elevational ascent
Valle de Siete Lagunas	2946	south	-	*F. fusca/lemani*	200 m
Laguna de Río Seco	3030	south	-	-	0 m
Laguna de Aguas Verdes	3070	south	-	-	0 m
Laguna Larga	2780	north	-	-	0 m
Ventisquero Morón	2809	north	-	*P. longiseta*	100 m
Laguna de la Mosca	2910	north	-	-	0 m
Cabecera del San Juan	2950	north	*P. longiseta*	*P. longiseta*	0 m
Collado Juego Bolos	3000	north	*F. fusca/lemani*	*F. fusca/lemani*	0 m
Los Panderones (Veleta)	3050	north	-	*P. longiseta*	100/150 m
Corral del Veleta	3100	north	-	-	0 m

Historical and current data on the presence/absence of formicids in cacuminal areas of Sierra Nevada.

Results

1. Coleoptera

The results shown that temperature increased significantly between the study periods at low and middle elevations (1.3 °C) but not at higher elevations (0.8 °C). Moreover, the distribution of dung beetle species exhibited important changes between time periods. Most species showed an increase in their mean elevation (89% of species, Figure 1). Changes in mean elevation were related to shifts at the lower elevational limit but not to shifts at the upper limit.

Changes in species elevational distribution were slightly higher than those predicted by changes in climate between study periods (Figure 2). However, differences between observed and predicted elevational changes were not statistically significant, suggesting that species are tracking changes in climate.

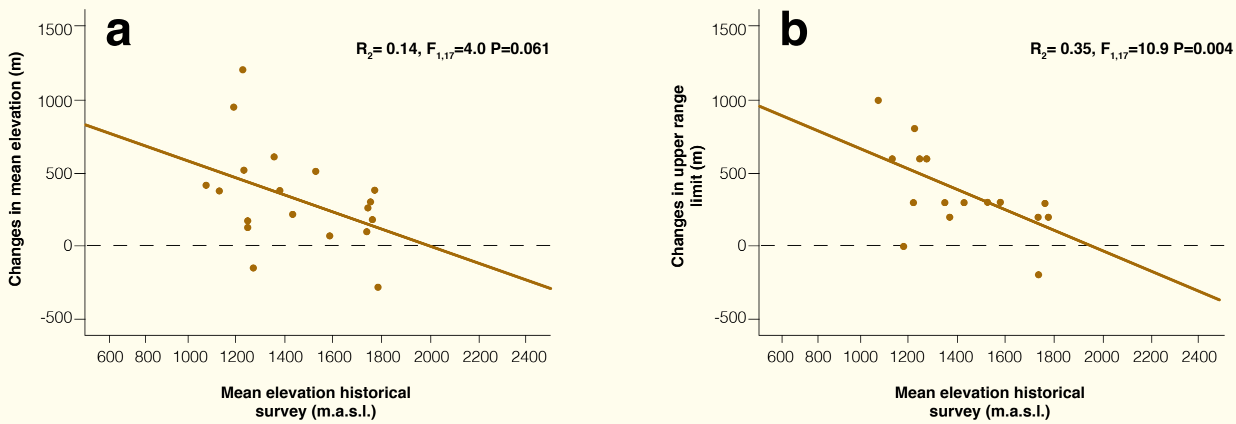
Most dung beetle species found in both time periods showed increases in their upper limit (17 out of 19 species). Shifts at the upper limit were negatively correlated with the mean elevation of the species during the historical period (Figure 2). Lower limits also moved uphill for most of the species (16 species) except for three species that moved downhill. Contractions at the lower limit and expansions at the upper limit were both consistent with changes in climate.

2. Lepidoptera and Hymenoptera

The historical data on the *Parnassius apollo nevadensis* show that this butterfly in 1971 (24 July) was very abundant in the access to Ragua Pass on both sides of the road some 2 km before reaching the pass (1950 m.a.s.l.). Sabariego de la Plaza and Aragonés de Inés [30] indicated that the San Juan Pass (2500 m.a.s.l.) marked the upper elevational limit for this species. Currently, this species reaches its population maximum around 2300 m.a.s.l. on the northern slope and around 2600 m.a.s.l. on the southern slope. Some specimens can be seen flying at 3000 m.a.s.l. on the southern slope, but there is no evidence that they reproduce at that elevation despite the presence of the host plant, however, we have not searched for larvae at those sites. The lower elevational limit can be situated currently at 1850 m.a.s.l. on the northern slope and at around 2200 m.a.s.l. on the southern one. These data indicate a rise in the upper limit of the species of around 400 m.

With respect to ants, the historical data reflect that *Proformica longiseta* and *Formica fusca/lemani* are the two formicid species that reach the highest elevations in Sierra Nevada. The rest of the formicid species usually have their upper limits some 300 to 400 m below these two species. The highest elevation that these two ants can reach in Sierra Nevada varies depending on the slope and the microclimate. In general, the historical data (during 1978) situated the upper limit of *Formica fusca/lemani* at 2900 m.a.s.l. at the head of the San Juan Valley (associated with the borders of the wet pasture-like areas *borreguiles* [29]) and at

Figure 1



Relationship of changes in a) the mean elevation and b) the upper limit of dung beetle species between survey periods against the mean elevation of the species during the historical period.

3000 m.a.s.l. at Laguna de la Caldera and Collado de Juego de Bolos [30]. While *Proformica longiseta*, more xerophilous than the other species, appears up to 2950 m. However, data for this species on the southern slope set the precise elevational limit below 2950 m.a.s.l., although the information is not as detailed. Historically two isolated populations of *P. longiseta* were known at the western slope of Puntal de Juego de Bolos (3050 m.a.s.l.) and near the Laguna de la Caldera (3060 m.a.s.l.), both populations are still currently present.

Populations of *Formica lemani* are currently present up to 3100 m.a.s.l. and for *Proformica longiseta* a population is present at 3140 m.a.s.l.. Thus, in the last 30 years both ant species have colonized certain points that were uninhabited in the 1970s, although this colonization is not uniform through the mountain range (Table 1). In conclusion, a general elevational ascent has been detected, this being as large as 200 m on the southern slope.

Figure 2

Average observed changes in dung beetle elevational distribution (mean elevation, upper and lower limits) and those predicted based on changes in climate (differences between observed and predicted changes were not significant).

› Discussion and conclusions

In Sierra Nevada, an elevational shift was found in the distribution of the insect species analysed, reflected in the elevational ascents in the upper and lower distribution limits. During this period of change, temperature also rose, especially in the low and middle zones of the mountain. Therefore, it appears to be highly likely that this response of the terrestrial insect species was triggered at least partially by global warming, resulting in the colonization of new climatically suitable areas at higher elevations.

This response is consistent with that observed in other regions for different groups of organisms, from plants to mammals [e.g. 31].

Species tolerance to the rising temperatures also appears to be the cause of lower limit contractions, although other factors such as habitat alterations or resource availability cannot be ruled out.

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› More references at http://refbase.iecolab.es/ref_dossier_resultados.html

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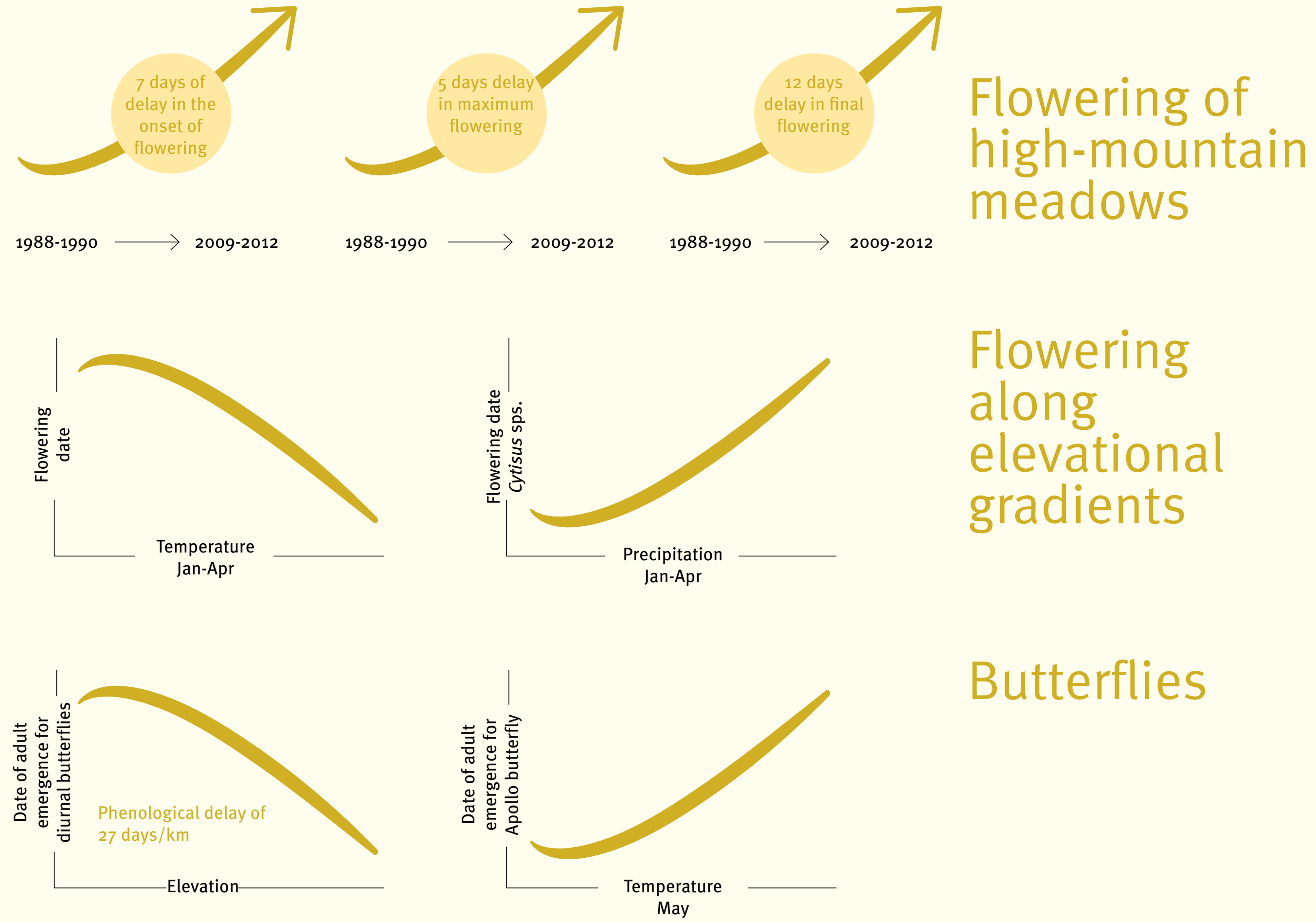
Chapter 6

The butterfly Medioluto Ibérico (*Melanargia lachesis*) drawing nectar from the flowers of European dwarf elder (*Sambucus ebulus*).

Phenology

Phenological alterations provided strong evidences of the effects of climate change on life cycles. Good examples are changes in reproduction and migration dates for birds, and changes in flowering and fruiting in plants. Elevational gradients of mountains offer good opportunities to analyse the consequences of shifts in climate on phenological processes. These responses are especially evident when broad time series of phenological data are available. In Sierra Nevada, there are phenological data on the flowering of vegetation in the high-mountain meadows (*borreguiles*). Analyses on the changes over the last 25 years show a delay in flowering date. This delay is especially noticeable in early-flowering taxa. The response found coincides with climate warming in Sierra Nevada (see Chapter 1). The response observed for plant species located



Graphical summary of the main results described in this chapter. It shows temporal trends for phenological attributes of species of *borreguiles* (high-mountain meadows). It also shows relationships between climate variables and both, flowering attributes of plant species and phenology of butterflies.

at middle and low elevations is highly variable between years and species. The early-flowering species respond by flowering even earlier in unusually warm years while late-flowering species do not respond in such a clear way, showing a closer relation with other factors, such as precipitation. In fact, species such as *Anthyllis cytisoides* respond quickly to low precipitation by flowering early.

For butterfly community the most frequent pattern observed was a delayed in the adult emergence date, mostly in higher elevations. For the Apollo butterfly, an emblematic species of alpine environment in Sierra Nevada, warm springs trigger earliness in adult emergence.

6.1. Changes in diversity, abundance and flowering phenology in plant communities: a 25-year study of high-mountain meadows (*borreguiles*)

Pérez-Luque, A.J.[1]; Sánchez-Rojas, C.P.[2]; Zamora, R.[1] and Bonet, F.J.[1]

[1] Andalusian Institute for Earth System Research. University of Granada [2] Environment and Water Agency of Andalusia

Abstract

High-mountain meadows (*borreguiles*) in Sierra Nevada are very sensitive ecosystems with respect to changes in water availability and temperature, serving as ideal communities to study climate change. A diachronic analysis of 25 years has revealed that these communities do not present significant changes either in composition or in species abundance. However, the phenological attributes do differ at the community level between the two periods analysed. In general, a delay in flowering was noted for the early-flowering species, which appear to be the most sensitive ones.

Aims and methodology

Changes in composition, abundance, and flowering phenology were analysed in the plant communities of the wet pasture-like communities (*borreguiles*) in two different periods: 1988-1990 and 2009-2012. For this purpose, permanent plots of 1 x 1 m were distributed in the *borreguiles* at the medium elevation site (San Juan) [1, 2]. The plots were visited every two weeks (from May to October). For each species, the presence/absence, cover, and number of flower structures were noted. With these data, flowering profiles were constructed and phenological indicators were established: onset and end of flowering, duration of flowering, and date of maximum flowering. Afterwards, changes were analysed for flower abundance (quantity of flowers) and flowering phenology at the community level, differentiating between early-, middle-, and late-flowering species. These comparisons were made for 19 taxa.

Results

At the community level, no significant differences were detected between the two periods in terms of species composition. In the period 1988-1990, the number of taxa was 23 as opposed to 32 identified at present, with 20 taxa detected in both periods. The abundance of flowering did not significantly change between the two periods at the community level. Nor were changes noted in flowering abundance for the early- or middle-flowering species. Significant changes were found only in flower abundance for two late-flowering species of the genus *Trifolium* (*T. pratense and T. repens*). On the contrary, significant changes were found for flowering attributes. At the community level, significant differences were found for all the flowering attributes between the two periods analysed (Table 1, Figure 1). The results show a mean lag of 7 days for the onset of flowering and of 12 days for the end of flowering. The period of maximum flowering was delayed a mean of 5 days. The late-flowering species did not present any changes in their phenological attributes between the two periods compared, while the early-flowering species showed significant changes for the onset and end of flowering as well as the date of maximum flowering (Figure 2).

Table 1

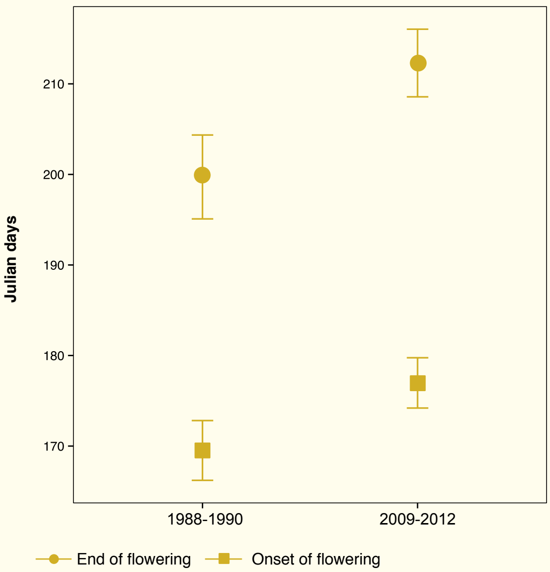
	p-value	Periods	Mean ± SD
Flowering onset	0.0001	1988-1990 2009-2012	169.52 ± 3.30 176.98 ± 2.78
End of flowering	0.0003	1988-1990 2009-2012	199.72 ± 4.63 212.30 ± 3.74
Duration of flowering	0.0312	1988-1990 2009-2012	30.20 ± 2.32 35.33 ± 2.50
Date of maximum flowering	0.0190	1988-1990 2009-2012	181.20 ± 3.91 186.16 ± 3.14

Mean values for different flowering attributes for the periods 1988-1990 (1990) and 2009-2012 (2010). The mean values and standard deviation are shown. Julian Day values are shown for all variables except for the duration of flowering expressed in number of days.

Discussion and conclusions

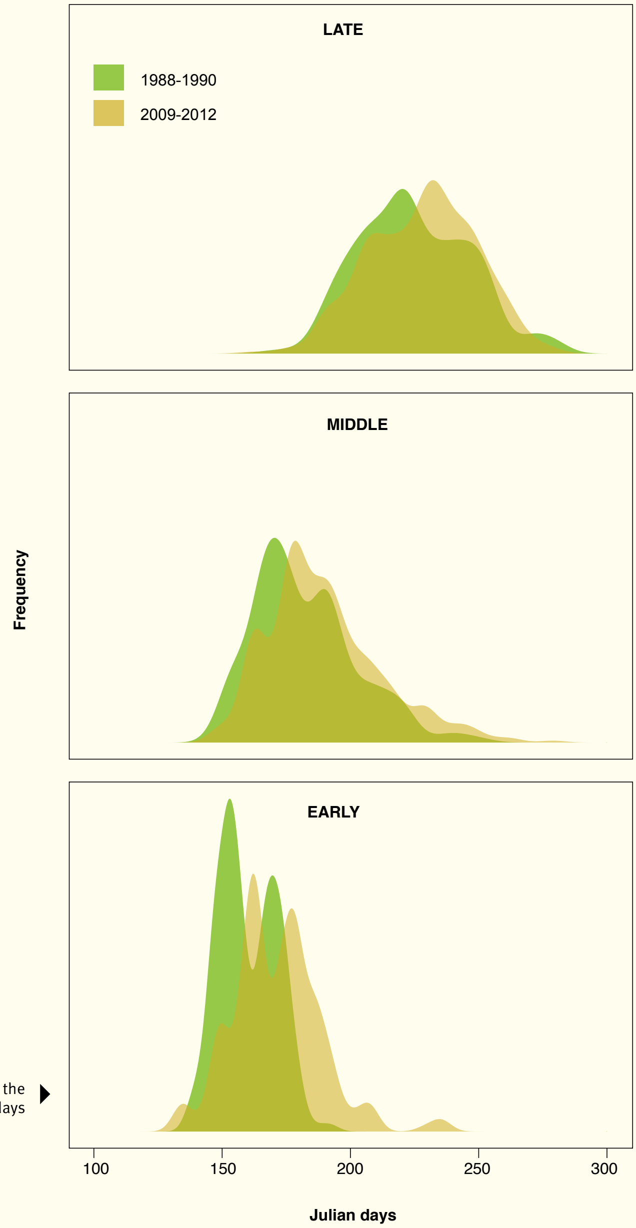
The taxonomic diversity found in the *borreguiles* was very high, both at the level of species as well as genera and families, as occurred in the summits of Sierra Nevada [3]. Our results showed no significant changes either in plant diversity or in flower abundance or in the *borreguiles* during the last 25 years. The close link of the borreguiles to the areas that remain wet all summer in the high mountain can determine the stability of the system studied. However, the flowering phenology has in fact changed between the two periods, although in different ways. A general delay was noted for all the phenological attributes analysed, a delay that proved statistically significant in the case of the species with the earliest flowering.

Figure 1



Day of onset (squares) and end of flowering (circles) at the community level between the periods 1988-1990 (1990) and 2009-2012 (2010). The date is indicated in Julian days (1 Jan: day 1; 31 Dec: day 365)

Figure 2



Flowering profiles for the periods 1988-1990 (1900; green) and 2009-2012 (2010; ochre) for the early- (lower), middle- (centre), and late-flowering (upper). The date is indicated in Julian days (1 Jan: day 1; 31 Dec: day 365)

6.2. Changes in flowering phenology along environmental gradients

Muñoz, J.M.

Environment and Water Agency of Andalusia

Abstract

Results for the flowering phenology of 13 plant species at 5 different sites in Sierra Nevada are shown. During the time of the study (five years), a significant earliness in flowering was detected in 2011, which was related to higher temperatures in the first months of the year. The response detected differed among species and between years. The silver broom *Adenocarpus decorticans* was the species with the broadest flowering range, while *Anthyllis citisoides* showed a special sensitivity towards winter precipitation, and *Genista versicolor* hardly differed between years.

Aims and methodology

The aim of the present monitoring was to determine the trend for flowering of some abundant and widely distributed species in Sierra Nevada. The flowering phenology for a set of species from different bioclimatic belts of Sierra Nevada was studied. For this purpose 4 fixed plots located in an elevational gradient were monitored during 5 years.The phenological status of each individual was recorded using a categorical scale: "-": without flowering,"0": with flower structures, "1": up to 5 flowers, "2": more than 5 flowers; "3": maximum flowering", "4": flowers and fruits, and "5": full fruiting. Each plot was visited between 5 to 9 times each year. The day of maximum flowering (MFD hereafter) was estimated by regression. The annual deviation of MFD with respect to the mean value of the series was used as the reference parameter to establish comparisons between years.
The results were compared with temperature and precipitation data between January and April for the study area (600 to 2150 m.a.s.l.).

Results

No clear trend was detected in the flowering phenology of the species studied, probably due to the need for a more extensive time series in order to explore the role of temperature and precipitation variations as key predictive variables. However, the intensity of the sampling enabled the establishment of relations between the phenological behaviour of the species studied and the climatic characteristics of the year (temperature and precipitation), and provided an understanding of the influence of elevation over flowering phenology in these species.

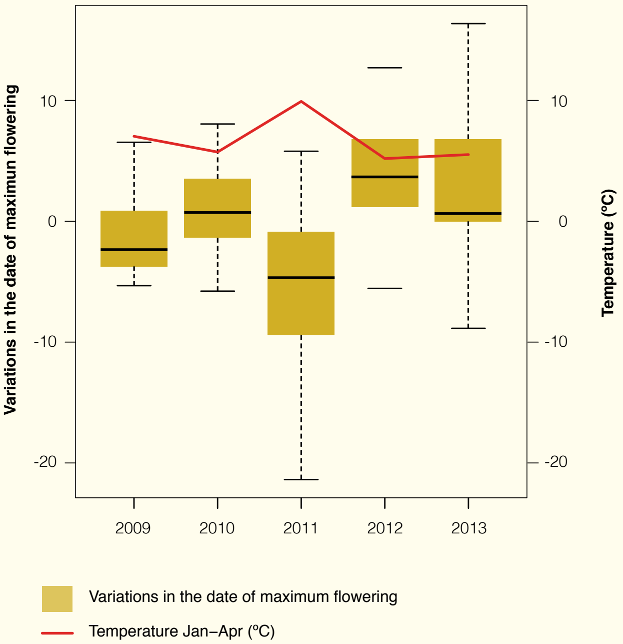
Temperature

Early flowering was found in the year 2011, when the highest temperatures were recorded in the first months of the year (Jan-Apr) in comparison with the rest of the series. The response to the higher temperature differed according to the species [4]. The early-flowering species (*Prunus dulcis, P. avium, Adenocarpus decorticans, Cytisus oromediterraneus*) showed the greatest earliness in flowering in 2011, while the late-flowering ones (*Anthyllis cytisoides, Genista umbellata, G. versicolor, and Retama sphaerocarpa*) did not show this behaviour.

Precipitation

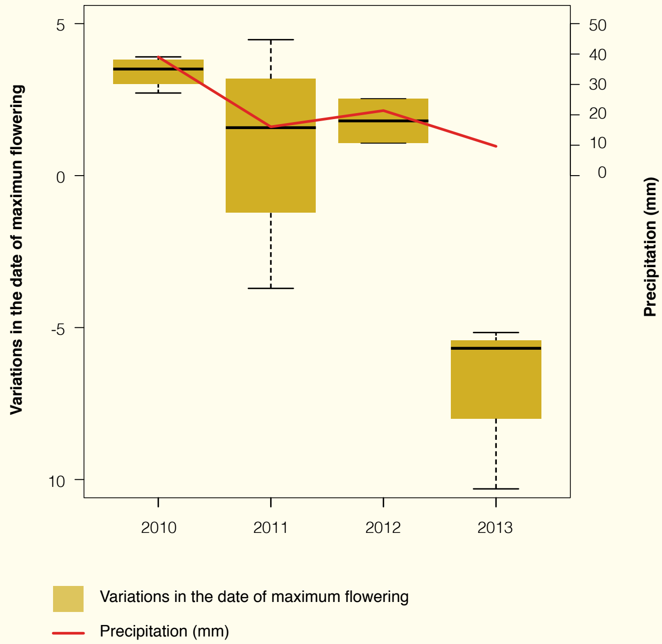
In the south-eastern part of the Sierra Nevada the sparse precipitation notably determined the flowering phenology. *Anthyllis cytisoides* flowered in these areas in years with low rainfall from January to April (Figure 2). Years with low precipitation in the beggining, only individuals at the upper elevation flowered, afterwards aborted and didn´t bear fruits.

Figure 1



Relation between the annual variation in MFD of the species studied and the mean temperature (red line).

Figure 2



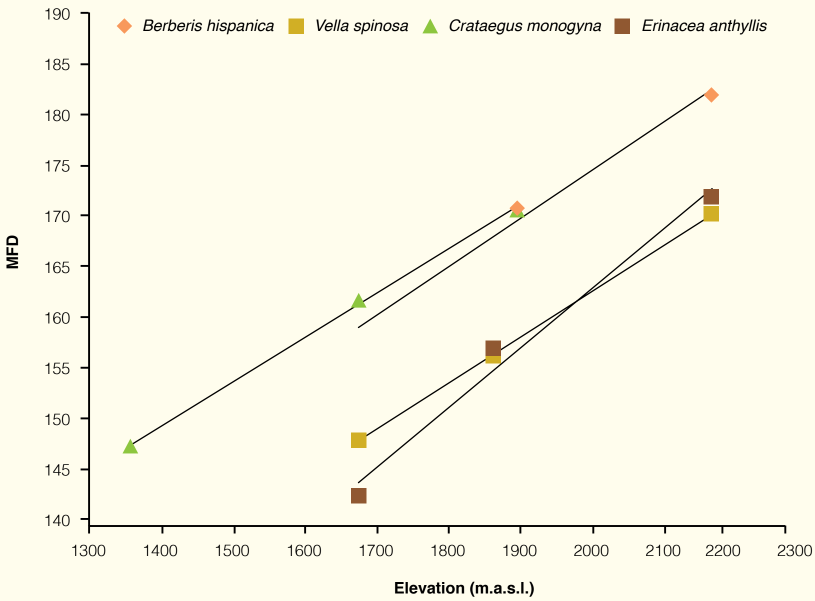
Relation of the annual variation in MFD of *Anthyllis cytisoides* and the accumulated precipitation during the months of January and April (red line).

Elevation

The elevational lag varied in each species. The rate of the shift was not uniform and often was recorded with delays of different magnitudes between sites situated at the same elevation but where the habitats differed. In 2013, the monitoring was undertaken with the intent of avoiding differences in habitat, resulting in a directly proportional relation between the MFD and elevation.

An elevational delay of 56.3 days/km was found for *Erinacea anthyllis* (r_s= 0.98, p=0.080), of 45.6 days/km for *Berberis hispanica* (r_s= 0.99, p= 0.060), 41.8 days/km for *Crataegus monogyna* (r_s= 0.99, p= 0.023), and of 43.3 days/km for *Vella spinosa* (r_s= 0.99, p=0.009; Figure 3).

Figure 3



Date of maximum flowering along an elevational gradient of *V. spinosa*, *C. monogyna*, *E. anthyllis*, and *B. hispanica* in 2013.

Discussion and conclusions

The response of the phenology of the different species to biophysical variables was heterogeneous. Of the 5 years in which flowering was monitored in Sierra Nevada, 2011 registered the highest temperatures in the first 4 months of the year. The expected earliness of the flowering was notable in the species with the earliest flowering while hardly influencing the flowering of the later-flowering species. Other factors apart from temperature, such as precipitation and elevation, strongly influenced flowering. The scant precipitation of the last few years has sharply depressed the number of flowers while causing the phenology of *Anthyllis cytisoides* to be earlier, this species being key in the landscape of the eastern sector of Sierra Nevada. These results have provided greater knowledge concerning the environmental variables that determine the phenology in different species of Sierra Nevada flora.

Cytisus galianoi in full flowering on the slope of the north face of Chullo peak.

6.3. The phenology of butterflies in Sierra Nevada

Barea-Azcón, J.M.
Environment and Water Agency of Andalusia

Abstract

The phenological study of butterfly communities of Sierra Nevada shows that most of the species delay their adult emergence at the sites situated at highest elevations. The species with later emergence periods (summer species) show greater synchronization over their elevational distributions than early species (spring species) do. A very clear relation has been observed between mean phenological delay over the elevational gradient studied. The results show that warm springs and, more specifically, higher temperatures in the month of May trigger early emergence of Apollo adults in Sierra Nevada.

Aims and methodology

Butterfly censuses

The sampling method consisted of visually counting the adult butterfly individuals along transects where all the butterflies were counted within an imaginary box of 2.5 m on each side and 5 m in front of and above the observer [5]. This is an internationally accepted method and is used in other similar programmes in different places around the world. The annual number of transects varied according to the year, between 8 and 22, and their length varied from 300 to 3272 m (mean: 1589.5 m). The transects were repeated a minimum of twice monthly and a maximum of once weekly. The samplings were made from 700 to 3100 m.a.s.l..

Butterfly phenology

Weighted mean date, for each year and for each species, was calculated as *mean date*: (Σ Number of butterflies per visit × Date)/Annual total number of butterflies of that species counted in that year and at that site [6]. Species that are not univoltine in the study area were not considered, nor were those that presented difficulties for field identification, or those that had overwintering adults, migratory species or tree-living species. From this information and from its regression against elevation of each study site, the phenological lag was inferred (expressed as days/km).

Climate data

To compare the effects of temperature on the phenological lag, data from the network of multiparametric stations in Sierra Nevada were used. The data corresponded to the stations of Encinar (1700 m.a.s.l.), Rambla de Guadix (600 m.a.s.l.), Embarcadero (1550 m.a.s.l.), Piedra de los Soldados (2150 m.a.s.l.), and Aljibe de Montenegro (975 m.a.s.l.).

For the effects of the climatology on the phenology of *Parnassius apollo*, a multiple regression analysis was performed. Mean date of adult emergence was used as dependent variable and mean temperatures and accumulated precipitation of April and June (monthly values and an average for three months) were used as predictions variables.

The Black-veined White (*Aporia crataegi*).

Results

Elevational gradient

The analyses included between 6 and 14 species/year, according to the criteria established. Only 6 species were analysed over the three study years. The proportion of species that showed a significant elevational delay or earliness was 83.3% in 2012, 71.4% in 2013, and 83.3% in 2014. In the year 2012, it was found that 5 of the 6 species showed a significant elevational delay in phenology. In 2013, 9 species showed a phenological delay along the same gradient, while 5 showed phenological earliness in relation to elevation. Finally, in 2014, 10 species showed a significant elevational delay in phenology while 2 showed the reverse trend. A common patern to all the years was that the species showing the greatest phenological delays were those with the earliest adult emergence (Figure 1). The phenological study of the 5 species of butterflies with a significant phenological response to elevation during the three study years revealed fluctuations between years (2012: 24.2 days of delay/km of ascent, 2013: 29.2 days of delay/km of ascent, and 2014: 27.4 days of delay/km of ascent). These oscillations were related to the mean temperature in March, April, May, and June (r_s= 0.99; p<0.001, Figure 2). The species included in this analysis showed different ecological profiles, although all of them have a mountain character: *Aporia crataegi* (mean elevation 2012-2014: 1746 m.a.s.l.), *Melanargia lachesis* (mean elevation 2012-2014: 1804 m.a.s.l.), *Hyponephele lycaon* (mean elevation 2012-2014: 2055 m.a.s.l.), *Lycaena alciphron* (mean elevation 2012-2014:2.055 m.a.s.l.), and *Parnassius apollo* (mean elevation 2012-2014: 2336 m.a.s.l.).

A specific case: the Apollo butterfly of Sierra Nevada

The results from the analyses of 6 years of data for *Parnassius apollo nevadensis* show that the day of the year on which the greatest number of adults emerged was subject to fluctuations from year to year, but the differences between sites situated at different elevations remained constant between years (Figure 3). The mean temperature of the month of May determines the earliness or delay in the weighted mean flight date of the Apollo butterfly at the site with the most complete data series, at Laguna Seca (r_s = 0.95; p<0.001, Figures 4 and 5). In this way, the warmest temperatures during May encouraged phenological earliness among adult Apollo butterflies at Laguna Seca, while cooler temperatures in the same month favoured a delay.

Discussion and conclusions

Elevational gradients in butterfly phenology in Sierra Nevada

The monitoring of butterflies in Sierra Nevada during the last 3 years has revealed that most of the species showed a significant elevational delay in phenology, although this response was not constant either among species or between years. The results show a mean delay of 26.93 days/km for 5 butterfly species with different ecological profiles and with significant trends from 2013 to 2014. Given that the temperature descends at a rate of 6°C per km of ascent in elevation, the results imply that for 1°C of increase in temperature, the phenology of a species will be 4.48 days early. Climate change prediction forecasts an increase from now to the end of the century of between 2 and 6°C for maximum temperatures and 1 and 4°C for minimum temperatures (Chapter 1), in the year 2100 the emergence of these insects could be approximately 6.7 to 22.4 days earlier.

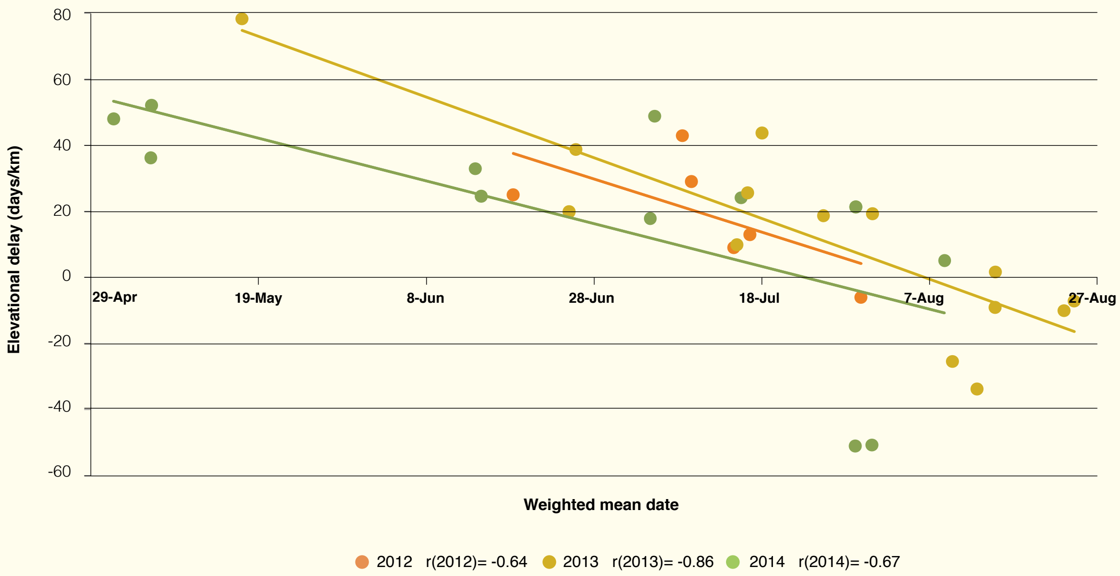
Despite the limitation of the time series available, a close relation has been established between the occurrence of warm springs (March-June) and the synchronization of adult emergence over the elevational gradients. This suggests that the climate warming at the local scale minimizes the differences in the phenophases of poikilotherms such as butterflies over the elevational gradient.

The specific case of the Apollo butterfly in Sierra Nevada

The mean elevational delay for Apollo butterfly populations in Sierra Nevada during the last 3 years was 45.2 days/km. The patterns observed at the site of Laguna Seca established a close relation between the warm months of May and phenological earliness but also indicated the reverse process. May is a key month for the Apollo butterfly in Sierra Nevada, since during this period the larvae of the 5th instar conclude their development and exponentially increase their size and weight (unpubl. data). The more hours per day provided by climatic conditions for the larvae to remain active, the greater will be their growth rate and the earlier they will pupate. This in turn can trigger early emergence of adults. In addition, during the series of years analysed, the May temperatures correlated positively with means of previous months (Feb-May, r_s= 0.81; p<0.05), this favouring larval activity and acceleration of larval growth and development.

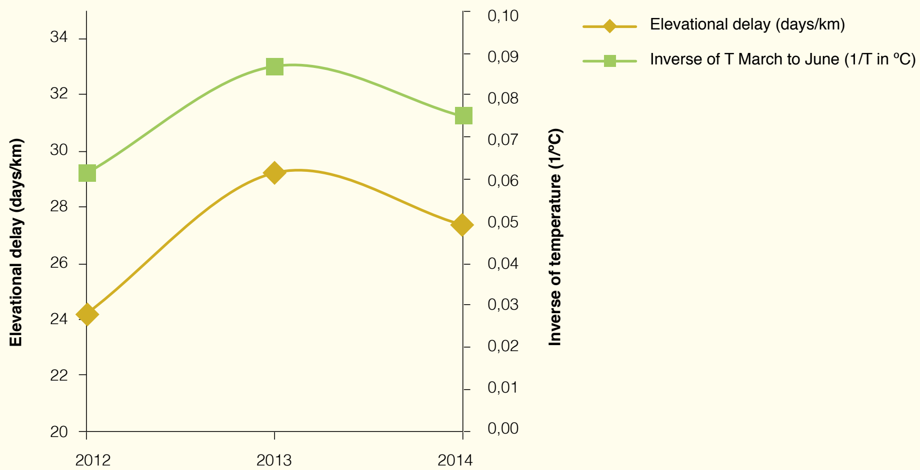
The data presented here provide evidence from two different standpoints (temporal and elevational gradients) concerning what are and what will be the repercussions of climate change on the populations of this key element in the insect communities of the Mediterranean high mountain.

Figure 1



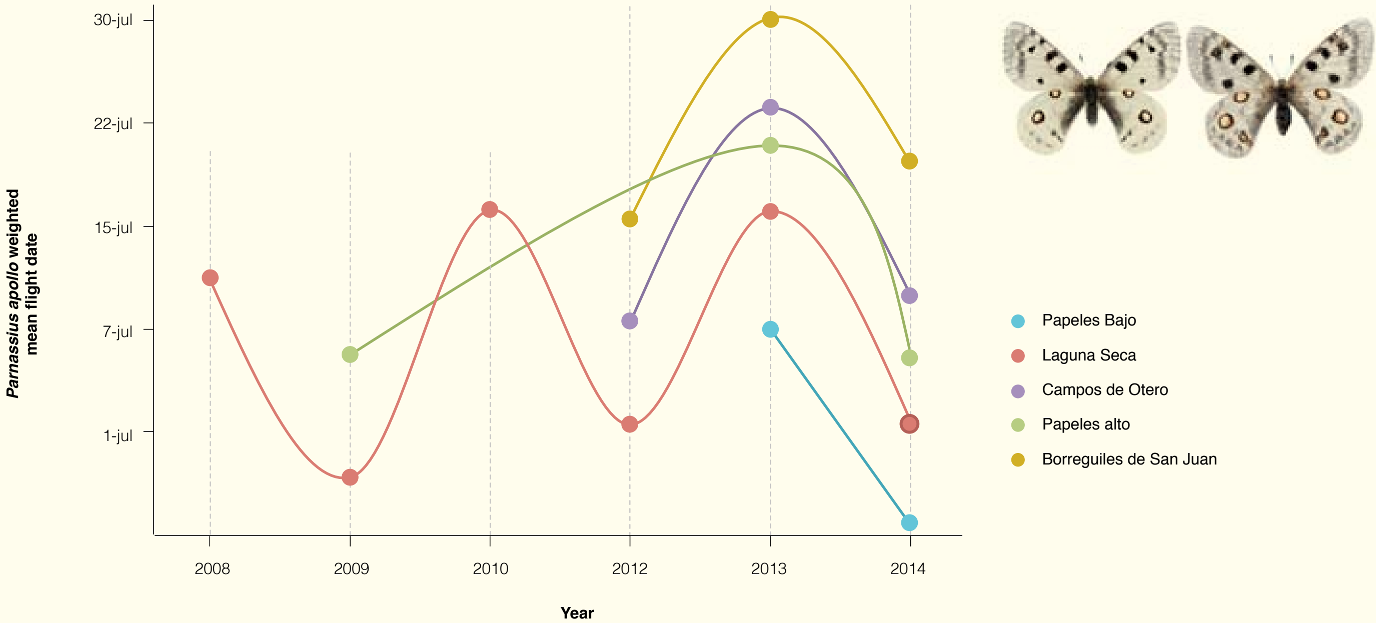
Linear regression of elevational delay and overall mean date. Each point represents one species and one year.

Figure 2



Mean elevational delay for 5 species (*P. apollo, M. lachesis, A. crataegi, H. lycaon, and L. alciphron*) of 2012 to 2014 and the inverse of the mean temperature of March to June (recorded at 5 weather stations located at between 600 and 2150 m.a.s.l.).

Figure 3

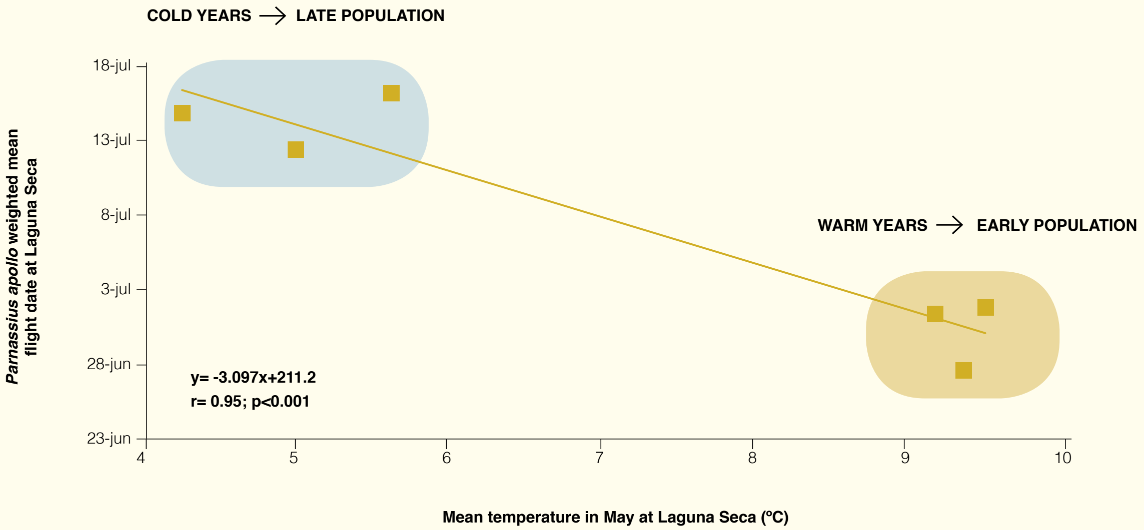


Parnassius apollo weighted mean flight date at different localities in 2008 (1 site), 2009 (2 sites), 2010 (1 site), 2012 (3 sites), 2013 (5 sites.), and 2014 (5 sites).

Figure 4

Parnassius apollo weighted mean flight date and mean temperatures in May at Laguna Seca.

Figure 5



Linear regression of the day of *Parnassius apollo* weighted mean flight date and mean temperature values for May at Laguna Seca.

Recently emerged *Parnassius apollo* with Laguna Seca (2280 m.a.s.l.) in the background.

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› More references at http://refbase.iecolab.es/ref_dossier_resultados.html

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Chapter 7

Aerial photograph in false infrared colour of the area burnt in the 2005 blaze.
The red colours indicate high photosynthetic activity.

Quantification of carbon flux in natural and disturbed systems

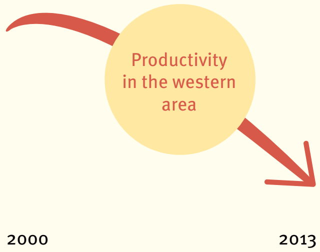
The evaluation of CO2 sources and sinks in different ecosystems has become an essential milestone to promote policies on managing climate change. The monitoring of primary productivity of the vegetation helps to understand the functioning of the ecosystem at different temporal and spatial scales.

Currently, relevant information is available on the role of forest ecosystems as a carbon source and sink in Europe. However, the information is far more scarce with respect to Mediterranean ecosystems, where not only the role of forests must be considered but also that of shrublands and extensive crops such as the olive plantations.

The Andalusian Regional Government is committed to fight against climate change and to abide by the Kyoto protocol together with the government of Spain through the creation of the Andalusian Strategy against Climate Change. Within this context, research has begun in order to quantify the flux of CO_2 assimilated or emitted by different Andalusian ecosystems.

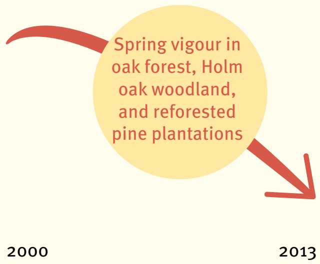
There are two basic techniques to quantify the quantity of CO_2 absorbed (or emitted) by ecosystems: the methods based on satellite images; and micrometeorological towers (*Eddy Covariance*), which provide direct field measurements of the CO_2 flow at the ecosystem scale. The use of teledetection for studying the ecological processes enable the researcher to work at greater scales and to analyse integrated biophysical processes from a functional perspective.

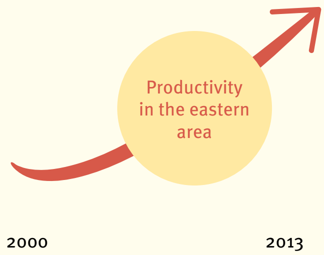
Thanks to the relation with net primary productivity, the spectral indices of vegetation are often used as surrogated of ecosystem functioning, such as the total annual carbon absorbed by the vegetation or seasonality and phenology of the dynamics of the carbon gains. These spectral indices can be validated with field data provided by Eddy towers. This enables the development of a monitoring system to evaluate trends over the long term and to detect spatial and temporal anomalies in the functioning of the ecosystems.



Maximum activity in May-June

in forest ecosystems



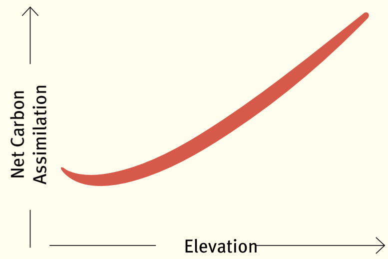


Minimum activity in winter

in forest ecosystems

Coupling snow/ productivity

in oak forests in the western part of Sierra Nevada, where early snow melt coincides with greater summer productivity



The most productive ecosystems are

oak forests and native Scots pine forests

Greater assimilation

of carbon in experimental plots where wood is not removed after a fire

Summary of the main results described in this chapter. The temporal evolution of productivity and greenness is shown, as well as the relation of the carbon assimilation with the elevation.

The main ecosystems of Sierra Nevada differ in their primary production values, but show similarities in their phenology, with maximums of photosynthetic activity in late spring (May-June) and minimums in winter. The most productive ecosystems are the Pyrenean oak forests of *Quercus pyrenaica*, native pine forests of *Pinus sylvestris* var. *nevadensis* and pine plantations.

The trends in the functional attributes of the Enhanced Vegetation Index (EVI) showed an elevational gradient and east-west orientation in Sierra Nevada. At the eastern part of the Sierra Nevada, an increase was detected in annual productivity whereas, in the centre and west, productivity diminished. This divergence is related to the two regional climate patterns operating in Andalusia, in which the NAO (*North Atlantic Oscillation*) exerts a stronger effect in the western part of the Sierra Nevada while the WMO (*Western Mediterranean Oscillation*) has a greater influence on the eastern part. *Quercus pyrenaica* forests, *Quercus ilex* woodlands, and pine plantations underwent a delay and loss of vigour at the beginning of the growth season (April).

Sierra Nevada ecosystems show great variability in the net annual carbon exchange, depending on the temperature and precipitation. The monitoring of three ecosystems situated at different elevations shows a net increase in carbon assimilation with elevation. Also, greater net assimilation was found in the experimental plots where wood was not removed after fires, indicating that the vegetation recovers earlier (and therefore improves its carbon-assimilation ability) when there is no post-fire intervention.

7.1. Changes in vegetation productivity according to teledetection

Alcaraz-Segura, D.[1,2]; Reyes, A.[2] and Cabello, J.[2]
[1] University of Granada [2] University of Almería

Abstract

The analysis of the time series of spectral indices of vegetation supplied by the MODIS sensor from 2001 to 2013 provides valuable results concerning the functioning (productivity, seasonality, and phenology of the dynamics of carbon gains) of Sierra Nevada ecosystems. The Pyrenean oak forests, the pine plantations, and the Holm oak woodlands show strong negative trends of greenness at the beginning of spring. Finally, an east-west gradient was detected in the greenness trend. In the west the annual production decreased while increasing in the east. This may be related to the climate patterns of precipitation at the regional scale.

Aims and methodology

The aim of this work is to detect and describe the changes in several attributes of the seasonal dynamics of carbon gains, indicators of primary production, seasonality, and phenology in Sierra Nevada ecosystems. For this, a number of temporal vegetation indices were used.

Spectral vegetation indices constitute the best tools for monitoring the primary productivity of ecosystems at the global level by satellite images [1]. These indices show a linear response with the fraction of photosynthetically active radiation intercepted by the vegetation (PAR). Because of this relation to primary productivity, spectral vegetation indices are often used to derive indicators of ecosystem functioning, such as total annual carbon absorbed by the vegetation or seasonality and phenology of the dynamics of carbon gains [2]. The images of the Enhanced Vegetation Index (EVI) were derived from the MODIS-Terra sensor between January 2001 and December 2013 (MOD13Q1 product). These images have a spatial resolution of 231 m and a temporal one of 16 days (23 images per year). First, the seasonal EVI curve was drawn for each year and the mean, maximum, and minimum EVI was calculated for each year. Next, the trends of these variables and in each compound were explored over the period 2001-2013 [3]. The trends were evaluated for the entire geographic context of Sierra Nevada, differentiating between the different representative ecosystems present in the protected area. The pure representative pixels of each ecosystem were selected from each ecosystem map of the Sierra Nevada Global Change Observatory.

Results

The main ecosystems of Sierra Nevada (Figure 1) differed in their primary annual production and seasonality but were similar in their phenology, with maximum photosynthetic activity values in late spring (May and June), and minimums in winter (except middle-mountain shrublands, the only ecosystem with minimums in summer). The most productive ecosystems were the *Quercus pyrenaica* oak forests, the native *Pinus sylvestris* forests, and pine plantations. The Holm oak woodlands and the native pine forests had intermediate primary production. The high- and middle-mountain shrublands registered low primary production values while the high-mountain meadows and rocky areas had the lowest. The ecosystems with the greatest seasonality were the high-mountain shrublands and the oak forests, while the least seasonality was found in the Holm oak woodlands and the conifer plantations.

The spatial pattern of the trends in the functional attributes of the EVI showed an elevational gradient and an east-west orientation (Figure 2). On the western edge of Sierra Nevada, increased annual productivity was found, while in the central and western sectors of the massif, this diminished. In general, the greater mean annual productivity (Figure 2a) resulted more from the higher minimums (Figure 2c) than from productivity maximums (Figure 2b). On the contrary, the lower mean annual productivity values (Figure 2a) were provoked more by lower maximums (Figure 2b) than by minimums in productivity (Figure 2c).

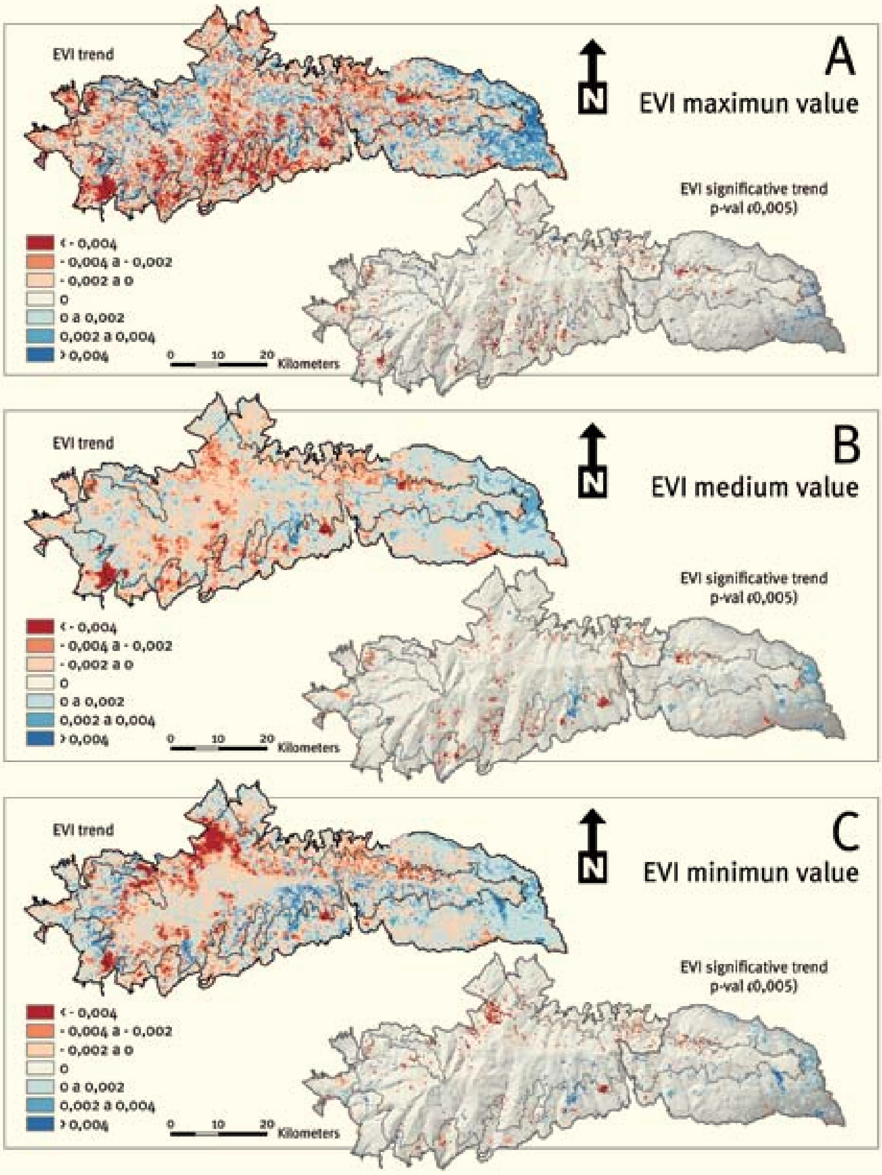
Figure 1

Seasonal dynamics and trend of EVI (Enhanced Vegetation Index) in the period 2001-2012. The left blue axis represents the mean seasonal dynamics of the EVI in the ecosystem. The red axis represents the average of the significant slopes found with the Mann-Kendall test (P<0.05).

Discussion and conclusions

Three of the eight ecosystmes analysed in Sierra Nevada followed heavily significant trends in carbon gains during the period 2001-2013 (Figure 1). The Pyrenean oak forests, the pine plantations and the Holm oak woodlands showed strongly negative trends in greenness at the beginning of spring, indicating a delay in the loss of vigour at the onset of the growth season [4]. In addition, the Pyrenean oak forests showed slightly positive trends at peak greenness in mid-autumn, indicating a delay in leaf senescence. The high- and middle-mountain shrublands showed similar trends towards a slight fall in productivity in spring and a modest rise in summer. The native pine forest was the ecosystem that presented the most stable photosynthetic activity during the period analysed. Finally, the annual EVI showed an east-west gradient. This divergence was related to two regional climate patterns that operate in this mountain range, the NAO exerting a greater effect on the western part of the Sierra Nevada (trend towards less productivity) and the WMO in the east (trend towards more productivity).

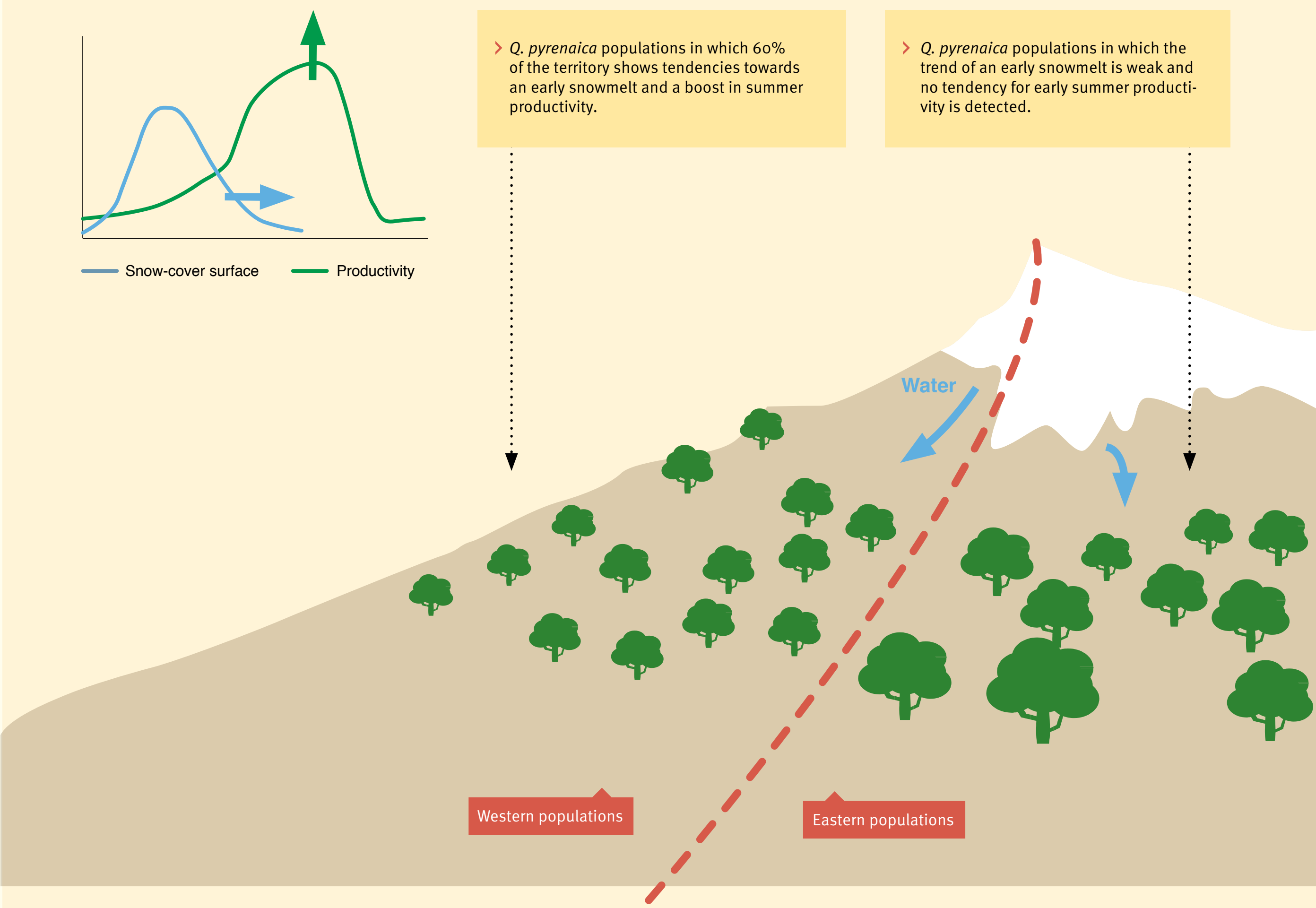
Figure 2



Spatial distribution of the trends of three indicators of the productivity estimators of ecosystem functioning derived from the EVI (Enhanced Vegetation Index) for the period 2001-2013. Trends in the a) annual maximum EVI, b) annual average EVI, and c) annual minimum EVI.

Relationships between snow and productivity of *Quercus pyrenaica*

Primary productivity depends on a multitude of biophysical factors. In mountain regions such as Sierra Nevada, the snow plays a determinant role. The quantity of water supplied by the snow can partly explain the functioning of nearby forest ecosystems at the tree line. A preliminary evaluation has been made for the relations between the snow and productivity in Pyrenean oak populations (*Quercus pyrenaica*) of Sierra Nevada. A coupling between primary production trends and duration of snow cover has been confirmed for the Pyrenean oak forests located in the western part of Sierra Nevada (Genil and Dúrcal river basins). In regions where the snow has a significant trend to melt early, productivity tends to increase in summer. This could explain why an early snowmelt provides water to oaks at the appropriate moment for their growth [5].



7.2. Exchanges of CO_2 and water vapour at the ecosystem scale

Sánchez-Cañete, E. P.[1]; Serrano-Ortiz, P.[1]; Oyonarte, C.[2]; Domingo, F.[3] and Kowalski, A.S.[1]

[1] Andalusian Institute for Earth System Research. University of Granada [2]University of Almería [3] Spanish National Research Council

Abstract

The monitoring of the exchanges of CO2 and water vapour helps provide an understanding of ecosystem functioning at different temporal scales. Results found across an elevational/bioclimatic gradient show the relevance of bioclimatic factors in the balance of the two and indicate the usefulness of long-term monitoring of CO_2 exchanges and water vapour as indicators of ecosystem functioning. Specifically, this study provides information on how Mediterranean ecosystems respond to climate change. This study also provides relevant information to optimise post-fire human action to favour ecosystem regeneration.

Aims and methodology

CO_2 exchanges provide ecosystem information concerning its behaviour as a source or sink of CO_2, enabling the discrimination of different phenological periods. In the growth period, the ecosystem assimilates more CO_2 than it emits, primarily due to greater vegetative development. However, there are other periods in which emissions predominate, mainly due to the senescence of vegetation together with accelerated degradation processes of organic matter and lower soil-water content, favouring the ventilation of CO_2 accumulated in soil pores [6,7].

The variations in the periods of CO_2 assimilation and emissions noted in different ecosystems are influenced by biotic factors such as vegetation and microorganisms; abiotic ones such as temperature and soil water content and anthropogenic ones, particularly perturbations caused by fires. Therefore, ecosystems situated in different bioclimate belts with certain conditions of vegetation types, soil, mean temperature, and precipitation, behave in dissimilar ways, showing different periods of fixation and emissions.

The aim of this work is to quantify and characterise the exchange of CO_2 and water vapour in Mediterranean ecosystems. For this purpose, ecosystems were studied on an elevational gradient with different bioclimatic conditions (precipitation and temperature; Figure 1). In an effort to understand the effect of the post-fire treatments, studies were also performed about CO_2 exchanges and evapotranspiration in two plots of burnt ecosystems with different management of the burnt wood (logging and non-intervention). These studies were conducted using *Eddy Covariance* towers able to record the assimilation and emission of CO_2 by the ecosystem and its evapotranspiration [8].

Results

Carbon balance under different bioclimatic conditions.

The results found in the three ecosystems studied for the hydrological year 2007/2008 show an increase in the assimilation period with elevation (Figure 2), which was associated with a net increase in carbon assimilation (Figure 3).

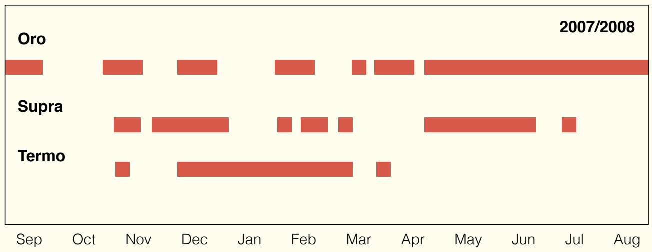
The most arid ecosytem, the thermomedite-rranean belt located in the Cabo de Gata-Níjar Natural Park, acted as a CO_2 source, emitting more CO_2 by respiration and soil ventilation than annually fixed by plants. As precipitation augments, despite the fall in temperature, the balance changes.

The ecosystem of the supramediterranean belt situated in the Sierra de Gádor acts practically in a neutral way, emitting slightly more than it fixes, while the ecosystem of the oromedite-rranean belt in the Sierra Nevada National Park serves as a CO_2 sink.

Figure 1

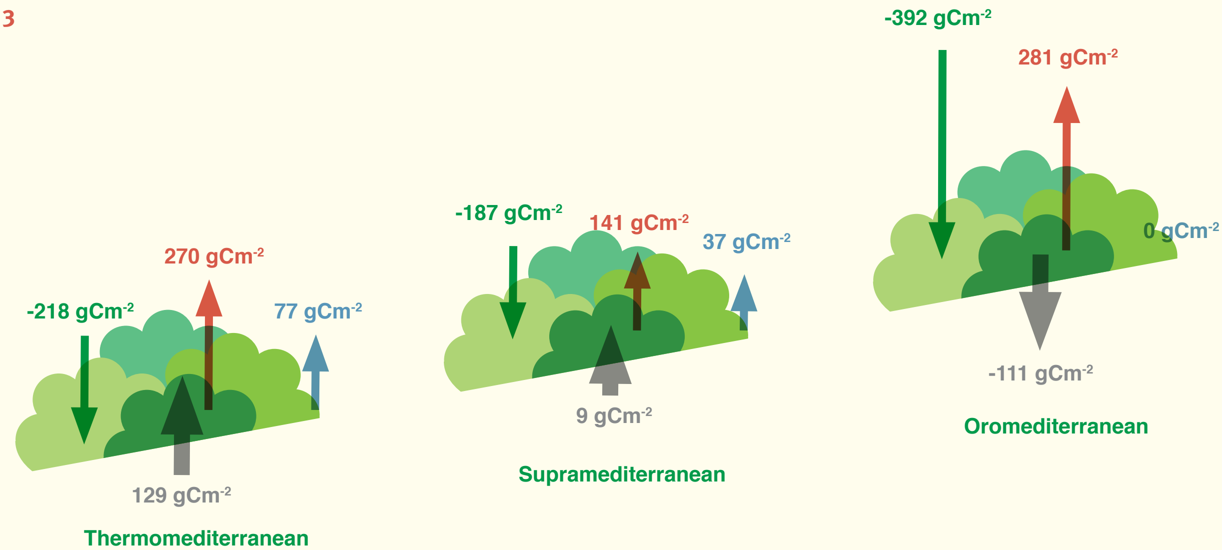
Images of the three study sites of this work. Left to right: thermomediterranean belt (Cabo de Gata-Nijar National Park), supramediterranean belt (Sierra de Gádor), oromediterranean belt (Sierra Nevada National Park).

Figure 2



Assimilation periods of three ecosystems of Mediterranean shrublands located in thermo-, supra-, and oromediterranean bioclimatic belts. These assimilation periods were defined as weeks with a net balance of carbon assimilation.

Figure 3



Carbon assimilated by photosynthesis (green arrow) emitted by respiration (red arrow) or by processes of soil ventilation (blue arrow) and total net exchange (grey arrow) in the hydrological year 2007/2008 by three ecosystems of Mediterranean shrubland located in the thermo-, supra-, and oromediterranean bioclimatic belts. The negative sign of the total net exchange denotes carbon fixation by the ecosystem.

Effect of post-fire treatment on the carbon balance

The different ways of managing burnt wood after a fire have direct impacts on the CO_2 and water balances of the ecosystem. In the area affected by the fire of 2005 on the hillside of Lanjarón, within Sierra Nevada National Park, 2 plots were established with different approaches to manage of burnt wood. One was called "No Intervention", where no action was taken after the fire and the burnt trees remained standing. The other was called "Removal", where the trunks were removed and the branches chipped. Three years after the fire, the "Removal" treatment acted as a CO_2 source, while the "No Intervention" treatment served as a sink registering a greater rate of evapotranspiration due to greater plant regeneration (Figure 4).

Discussion and conclusions

Mediterranean ecosystems show great variability in the net annual exchange of carbon, from acting as sources of approximately 120 g cm^{-2} (thermomediterranean) to serving as sinks of equal magnitude (oromediterranean). The ecosystem located in the thermomediterranean belt shows a continuous growth season during the winter when water availability and temperatures allow net carbon assimilation. During the rest of the year, before the lack of water and the high temperatures, the adaptive mechanisms of the plants are activated, such as the stomatal closure, resulting in a decline in assimilation, without photosynthesis recovering during the sporadic precipitation events as occurs in other ecosystems. In the supramediterranean ecosystem, an increase in precipitation and a decrease in temperatures translate as discontinuous growth periods that extend almost all year long, except for the hottest and driest summer months and part of the coldest months. In the oromediterranean ecosystem, the assimilation occurs almost during the entire year except for the months when the ground is covered by snow. This increase in growth periods and net carbon assimilation with elevation could be related to different behaviour of photosynthesis and respiration processes in relation to temperature. Although a fall in temperatures causes a loss in photosynthetic efficiency, this limits even more the respiration processes of the soil, and therefore even in the coldest periods, with low biological activity, the carbon assimilation predominates [9].

Finally, with regard to the post-fire treatments, several arguments could explain the net carbon assimilation in the "No Intervention" plot as opposed to the "Removal" plot three years after the fire [10]:

1) "No intervention approach" improves soil fertility. The burnt wood of the trees and the woody remains represent an enormous reserve of nutrients left *in situ* to be progressively incorporated into the soil.

2) "No intervention approach" improves microclimatic conditions. The effect of the burnt trees and limbs alter the micrometeorology, facilitating plant regeneration.

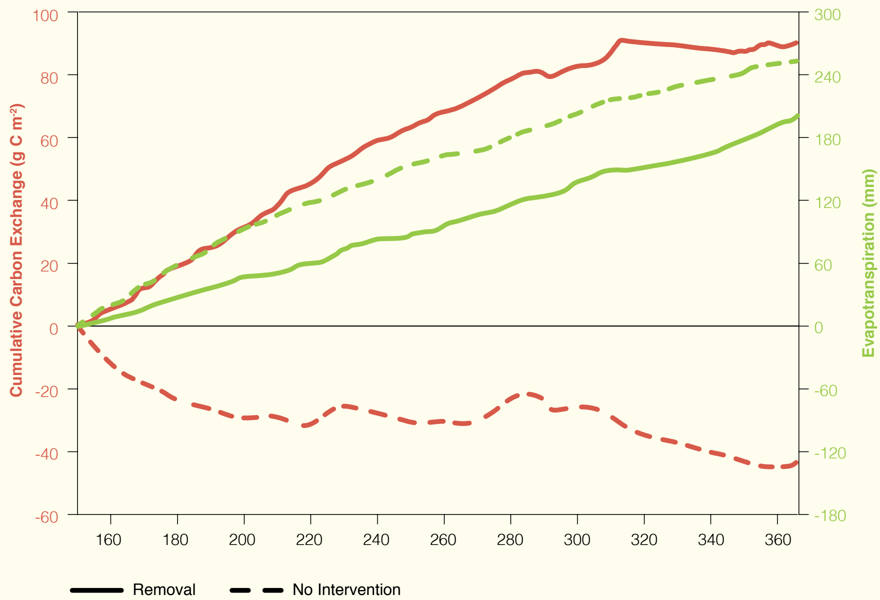
3) Wood removal negatively affects regeneration, damaging the seed bank and seedlings thereby reducing plant density.

4) The presence of trunks and branches reduces herbivory.

5) The dead material reduces erosion, minimizing runoff.

6) The site attracts seed dispersal by birds.

Figure 4



Quantity of carbon emitted to the atmosphere (g C m^{-2}) and evapotranspiration (mm) in the post-fire treatments of "No Intervention" (dashed line) and "Removal" (solid line) from June to December.

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› More references at http://refbase.iecolab.es/ref_dossier_resultados.html

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Chapter 8

Towards adaptive management practices in the forests of Sierra Nevada

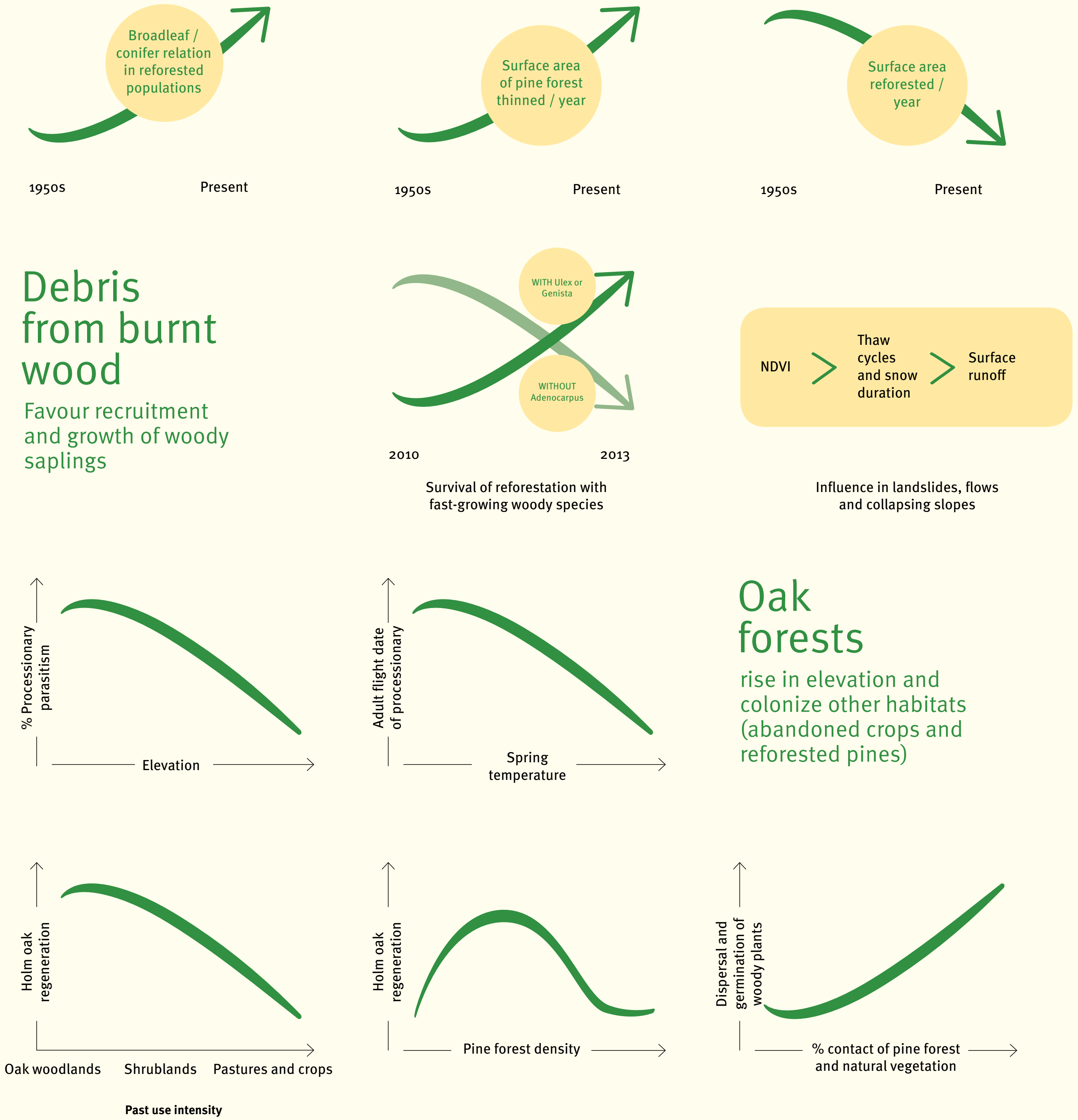
Oak forests are strategic socio-ecosystems for the intense exploitation that they have endured throughout their history as well as for their extraordinary ecological value. The populations of Sierra Nevada suffer the effects of drought and the rise in temperatures provoked by climate change.

Currently, forests face shifting climatic conditions, with a temperature rise predicted to be between 1.5 and 2ºC by the end of this century, a reduction in precipitation and an increase in atmospheric CO_2. From the Sierra Nevada Protected Area, adaptive management has been launched, combinig the existing scientific knowledge on ecosystems with the experience acquired in the field.

This chapter summarizes what has been learnt to date with this philosophy, highlighting a series of management recommendations that may be applicable in other Mediterranean forest ecosystems bearing similar characteristics.

First, a retrospective synthesis is presented for the main actions taken in forests of Sierra Nevada from 1935 to the present. The information compiled enables an evaluation of the time evolution of variables such as surface area of reforestation / year, density of the reforested populations, the of broadleaf / conifer proportion, and the surface area thinned. In the past the greatest effort was dedicated to pine reforestation over large surface areas, while current investment goes to improving the structure of the stands to favour their development and bolster their resilience. As a novel example of one of these actions, the results are presented for a restoration programme performed in the area of Lanjarón after a fire in 2005. This experimental restoration was based on fomenting the spatial heterogeneity in the landscape and on the functional diversity of the species used, as well as on bolstering the successional recovery mechanisms of the communities. The monitoring of this restoration reflects the importance of making use of the elements that may grow naturally after a fire which can facilitate the natural regeneration and the survival of shrubs and trees.

In addition, an analysis of the dynamic of a forest pest is presented, the pine processionary (*Thaumetopoea pityocampa*). This species has been expanding while intensifying the frequency of



Graphic summary of the main results presented in this chapter. Changes in forest management and issues related to the post-fire vegetation response are presented together with the influence analysed from certain variables in soil loss, the behaviour of the pine processionary, and the functioning of Pyrenean oak, Holm oak, and pine forests.

its attacks over recent decades [11-12]. Climatic change affects both its phenology (accelerating its development) as well as its distribution (prompting it to ascend in elevation, where it has fewer natural enemies). In this situation, a prevention strategy is proposed based on habitat management together with planned development of structurally and taxonomically diverse forest formations. This forest configuration is more resistant to pests and other forest-decay processes.

A series of management recommendation for pine plantations are offered based on results provided by several scientific studies. The environmental variables (climate, altitude), the landscape structure (fragmentation, size, and density of pine stands, as well as position and contact of the native patches of vegetation), and past land use largely explain both the structure (diversity) as well as the functioning (regeneration) of the pine plantations.

Similarly, management recommendations to facilitate the expansion of *Quercus pyrenaica* forests in Sierra Nevada are shown. These forests are highly vulnerable because they are at the southern range limit.

All these criteria and recommendations are directed, ultimately, towards favouring the adaptation of Sierra Nevada forests to global change and thereby guaranteeing the goods and services that these currently provide. The maintenance or even expansion in the forest cover is crucial, given the forecasts for increasing torrentiality of rainfall due to climate change, which could result in a greater number of landslides and rockfalls.

River Monachil valley, where oak forests mingle with reforested pines (above left).

8.1. History of Sierra Nevada forest management: implications for adaptation to global change

Bonet, F.J.[1]; Aspizua, R.[2] and Navarro, J.[3]

[1] Andalusian Institute for Earth System Research. University of Granada [2] Environment and Water Agency of Andalusia [3] Andalusian Regional Ministry of Environment and Spatial Planning

Abstract

The implementation of adaptive management plans for forest resources requires, among other things, the evaluation of forest-management effectiveness. This is even more vital in a context of global change, since the uncertainty concerning the response of ecosystems to the actions is greater. In this sense, a spatial catalogue has been designed for forestry actions undertaken in Sierra Nevada from 1935 to the present. This information enables the evaluation of the time course of variables such as the reforested surface area per year, the density of the reforested stands, or the broadleaf:conifer ratio in the reforested populations. The reforested surface area per year has continued to follow a clear decreasing trend from the 1970s to the present. Also, an increasing trend has been detected in the broadleaf:conifer ratio in reforested stands. Finally, an overall index of forest management has been designed for Sierra Nevada. This index takes into account the type of action, its intensity, and also the timespan between its application and the date of calculating the index. This index shows in a synthetic way the intensity of forest management in Sierra Nevada, which has been decreasing since the 1960s.

› Aims and methodology

The aim of this work is to analyse the forestry actions conducted in Sierra Nevada, considering the temporal component (data series from 1935 to 2014), the spatial one (spatial representation of the stands acted upon) and the types of actions (reforestation, thinning, post-fire restoration). This shows different spatio-temporal patterns of the forestry actions, providing an assessment of their relation to the prevailing forestry policies at each stage [1], as well as deeping in knowledge concerning land-use changes [2]. A two-phase methodology was applied:
a) Gathering information on forestry actions and including them in a data base, considering that this information has different formats and appears in different sections of public administrations in charge of this forestry material. Since 1990, there has been a registry on paper of the forestry actions taken. This registry contains information on the different stands treated (reforested, thinned, cleared, pruned, etc.), as well as their characteristics (intensity of the action, species planted, etc.). b) Analysing and interpreting the existing information.

› Results

The following variables were analysed in relation to the management of Sierra Nevada forests over recent decades (Figure 1):

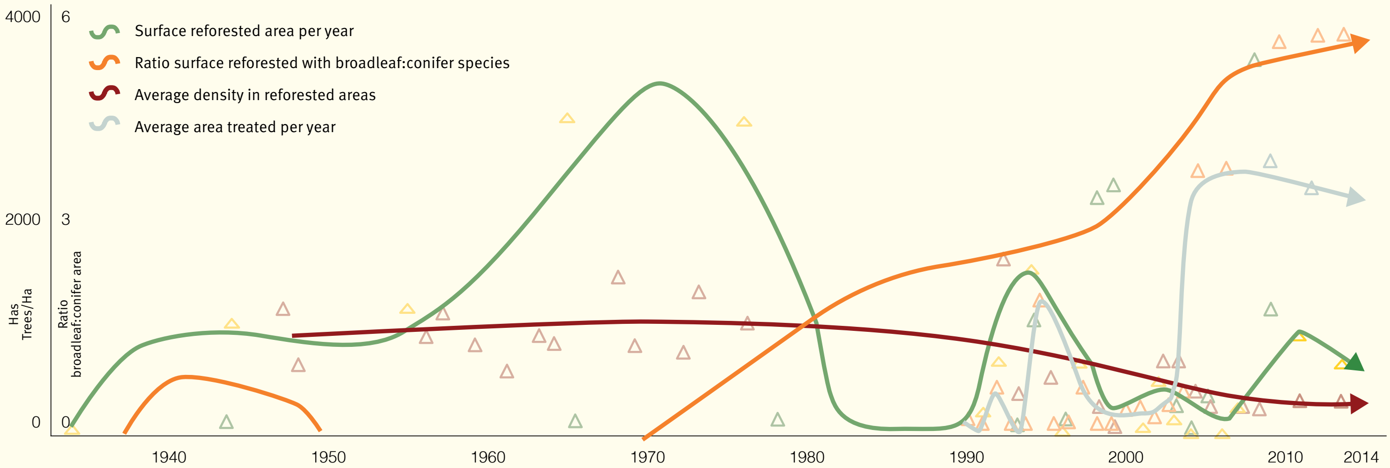
Reforested stands:

- Progress of the reforested surface area per year. This variable indicates how the reforesting effort by the environmental administration changes through time. A maximum was reached between the 1960s and 1970s. In this period, about 3,000 ha per year were planted. At present the reforestation rate is far lower, in no case reaching 500 ha per year.
- Development of the ratio reforested broadleaf:conifer surface area. The results clearly indicate a rise in the amount of surface reforested using broadleaf species.
- Development of planting density. The data available also reflect a clear trend towards a lower density of the reforested populations. This gives an idea of the types of projects performed, which are steadily more specific and adapted to needs of each territory.

Forest treatments:

- The time course of the surface area treated by thinning/clearing and pruning has been analysed from 1990 to the present. This variable greatly fluctuates. No clear trend was discernible.

Figure 1



Temporal evolution of the reforested surface by year (green), the broadleaf:conifer ratio (orange), the average density of the reforestation (red) and the thining/cleaning surface per year (gray) in Sierra Nevada from 1930s to present.

Forest-management index for Sierra Nevada:

- An index was proposed to summarize the intensity of forest management in Sierra Nevada. This indicator represents the degree of management to which the Sierra Nevada forest ecosystems are subjected by the Environmental Administration. The indicator is an useful tool to visualize the intensity of the territorial management.

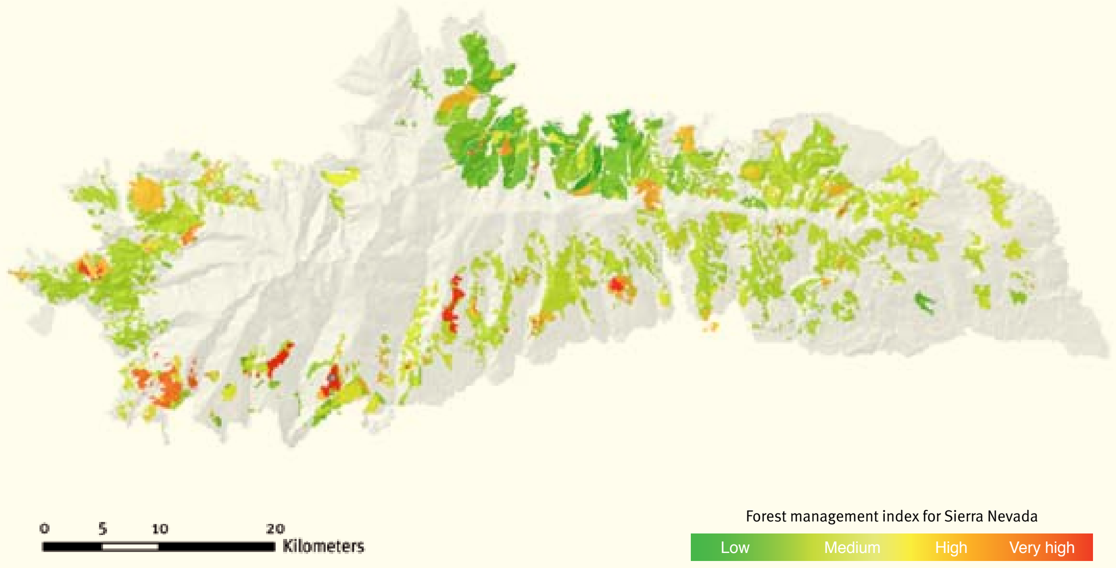
This index is calculated by assuming that the degree of management is greater the more intense the action at the time of execution (reforestation›tree thinning/clearing › shrubland thinning › branch thinning› pruning › waste removal). This effect is attenuated linearly over time. That is, the longer the passage of time, the lower the intensity of management in a given period.

Figure 2 shows the spatial distribution of the forest-management index in 2014. The red sites are those that have either undergone more intensive or more recent actions. Most of the zones that underwent action have a low degree of management (green tones). These correspond to the large reforestation areas established in the 1960s and 1970s.

View of the reforested pines of Marquesado del Zenete.

Distribution of plants with pack animals in Laujar de Andarax, April 2009.

Figure 2



Map showing the index of Sierra Nevada forest management in 2014. Green color indicates a low degree of management, while red indicates a high degree of management.

Discussion and conclusions

Figure 1 indicates that the first reforested efforts began in the 1930s and 1940s [3]. From 1954 on, with the creation of the Forest Hydrological Service, there were two decades of very intense reforestation, which reached some 2000 ha per year. More recently, the only noteworthy reforestation peaks correspond to fire restoration, as occurred in 1995, when 1,300 ha were reforested out of the 2,000 ha that burnt in 1994 in the South part of the mountain or after the blaze of more than 3,000 ha in the Southwest in September 2005. From the end of 1970 to the present, there has been a change in reforestation policy. Previously, vast reforestation projects were implemented with the specific aim of reducing soil loss in the territory at the same time as promoting rural employment [4]. Currently, reforestation is considered as a response to impacts on the plant cover, such as fires or other catastrophic events, but also as a way to diversify and reinforce the forest cover. On the other hand, it is also evident (Figure 1) that the reforested broadleaf:conifer ratio has risen. Except for sporadic planting of acorns in the 1940s [5], the rest of the reforestation until the 1990s used conifers as the main species, a situation which has been reversed at present, with broadleaf species predominating over conifers. The greater availability of resources for reforestation, less reforested surface area per year, and advances in the scientific knowledge and techniques regarding the ecology of the Mediterranean forest could explain for the increased use of broadleaf species and the consequent diversification of the reforested stands. Also, a clear trend can be observed towards reducing the planting density, shifting from a density of greater than 2000 trees/ha in the 1960s and 1970s to 500-600 trees/ha at present.

Finally, the forest-management index (Figure 2) accurately synthesises the management trends above mentioned. The intensive reforestation of the 1960s and 1970s tincreases the management index, which from this point begins to descend not only in terms of actions undertaken over a smaller surface area, but also less intense measures implemented (lower reforestation density, lower rate of reforested individuals as opposed to other types of lower-intensity forestry action, etc.). However, with respect to recent actions, it bears emphasizing the efforts made to thin extensive areas of pine forests in Sierra Nevada between 2005 and 2014, funded mainly by the Council of the Environment and Land Management with co-financing from the European Union. However, the index does not include the linear preventive treatments against fires (manual or mechanized, primarily in firebreaks), which are undertaken regularly and throughout the mountains.

Evolution of the main actions of forest management in Sierra Nevada

A summary of the most significant qualitative differences between past and present forest management of Sierra nevada is shown below. This results from the analysis of the database of forestry actions and information collected from interviews to officials from the Environmental Agency, managers and those responsible for the main actions.

1950-2000	2000-2010
REFORESTATION	
• Greater reforested surface area. Aim: hydrological-forest restoration at basin level, accompanied by engineering management of the river courses. • First phase: Manual planting. Second phase: mechanized preparation of the land (terracing). • Greater planting density (>2,000 trees/ha). • Regular planting distribution (square or staggered pattern, frequently in terraces). • Predominance of conifers as opposed to broadleaf species, mainly *Pinus halepensis* and *P. pinaster* in the low areas and *P. nigra* (sunny exposures) and *P. sylvestris* (shady exposures) in the higher areas. Almost exclusive use of tree species. • Often combined planting (1-2 years) with seed in the same hole. • Predominance of plants from allochthonous seed. • Plants from nurseries located on the same mountain, with rudimentary production systems. Previous acclimation to local conditions. • Directly performed by the Forest Administration.	• Smaller reforested surface area. Aim: mainly post-fire restoration of forests and dispersal centres for stand diversification. • Manual or mechanized planting according to demands of the terrain, without terracing. • Lower planting densities. • Irregular planting distribution, often in copses. • Greater proportion of woody broadleaf species (trees and shrubs) belonging to the floristic group accompanying the natural plant association of the area. • Predominance of planting *vs*. sowing. • Plants from a traced origin, with local varieties given priority. • Plants from centralized nurseries with more advanced production systems. Plants without previous acclimation to local conditions. • Executed by public or private enterprises.
FORESTRY TREATMENTS OF PINE FORESTS	
• Minor thinning during the first reforestation stage: elimination of double trunks and pruning with hatchet, especially near roads. • Scattered thinning for commercial purposes in the 1980s and 1990s.	• From the 1990s on, thinning over a greater surface area, with predominance for conservation (control of competition and diversification of the stand) and preventive aims. • Gradually the pattern becomes more irregular, seeking to break the uniformity of the stand. Systematic felling gradually gives way to the combination of cutting of different intensities, predominantly 30-50% of the trees removed.
BRANCH THINNING AND PRUNING OF BROADLEAF SPECIES (HOLM AND PYRENEAN OAKS)	
• Done by the local population to obtain firewood.	• Done mainly by the administration for conservation and prevention. Secondary use as fuel.
INFRASTRUCTURES TO SUPPORT THE MANAGEMENT OF FOREST (NOT INCLUDED IN THE FOREST-MANAGEMENT INDEX)	
• Construction of pens above the reforestation line to support livestock use of the peaks. • Opening of practically the entire network of roads and service routes to support forestry activity. • Acquisition of terrain, mainly abandoned agricultural land, for property of the state administration and for reforestation. Consortium with the city halls that give rise to the public mountain areas of the city halls.	• Scattered construction of pens. Maintenance, improvement, and adaptation of the existing ones to the landscape. • Maintenance and improvement of the existing network of roads and service routes. • Purchase of parcels with special interest for conservation with the creation of the Sierra Nevada Protected Area (total 6.184 ha)

8.2. Design and monitoring of a post-fire restoration

Zamora, R.[1]; Bollullos, C.[2]; Aspizua, R.[2]; Cabezas-Arcas, F.M.[1]; Castro, J.[3] and Navarro, J.[4]

[1] Andalusian Institute for Earth System Research. University of Granada [2] Environment and Water Agency of Andalusia [3] University of Granada

[4] Andalusian Regional Ministry of Environment and Spatial Planning

Panoramic view from the burnt area of the municipality of Lanjarón. In the foreground the *Thymus-Brachypodium* thicket can be seen recolonizing the burnt terrain.

Abstract

In September 2005 a fire in Sierra Nevada affected more than 1,100 ha of reforested pines. Afterwards, an ambitious restoration programme was implemented by researchers from the University of Granada in collaboration with the managers of the Sierra Nevada Protected Area. The design of this project applies the most recent scientific knowledge to promote a new model of ecosystem restoration. The key points of this restoration are: 1) promoting spatial heterogeneity, 2) encouraging functional diversity, and 3) promoting the natural recovery capacity.

Aims and methodology

The restoration project designed after the fire takes advantage of natural succession dynamics, promoting both the spatial heterogeneity as well as the species diversity. The objective is to favour a more heterogeneous and diverse landscape, able to resist possible catastrophes (pests, forest decay, fires) with a greater adaptive capacity to climatic change.

In the project, different restoration techniques were applied, such as using pioner shrubs and vegetation debris as planting microsites, and creating dispersal core areas to strengthen the recuperation of the most degraded areas after the fire. For the creation of these new core areas, shrubland species of rapid growth and reproduction were used, such as, *Rosa canina, Crataegus monogyna, Prunus ramburii, P. spinosa*, and *Berberis hispanica*. In addition, planting takes advantage of pioneer shrubs that appeared spontaneously after the fire, mainly *Adenocarpus decorticans, Ulex parviflorus, Genista versicolor*. These species can act as nurse plants, enhancing the survival of reforested seedlings. This novel technique of restoration has been tested in Sierra Nevada, with very positive results [6].

Furthermore, in a sector of the burnt area, some experimental plots were established with three treatments differing in the management of the burnt wood: the traditional removal of all trees standing after the fire, no intervention (leaving all trees standing with no action), and an intermediate action of felling and cutting up 90% of the trees but leaving the entire biomass *in situ*. Since then, several variables have been monitored, these being related either to vegetation regeneration (survival, growth, herbivory damage) or to ecosystem functioning (recuperation of species diversity, carbon sequestering, burnt-wood decomposition, etc.).

Holm oak seedling growing under the remains of burnt wood left after the fire in the experimental plots.

Results

The presence of pioneer shrubs have generally favoured the survival and growth of most of the introduced species, although it has had a markedly different effect on survival depending on the species. The thorny species formed by *Ulex parviflorus* and *Genista versicolor* have facilitated the restoration, improving the survival rates of all the species by substantially reducing ungulate herbivory.

On the contrary, the effect of *Adenocarpus decorticans* on the survival of *B. hispanica, C. monogyna, P. spinosa* or *Q. ilex* has not been beneficial (see Table 1).

The survival and growth of seedlings was also affected by elevation, this generally being greater at high altitudes for *Q. ilex* and *B. hispanica*, while the other species prospered better at low elevations.

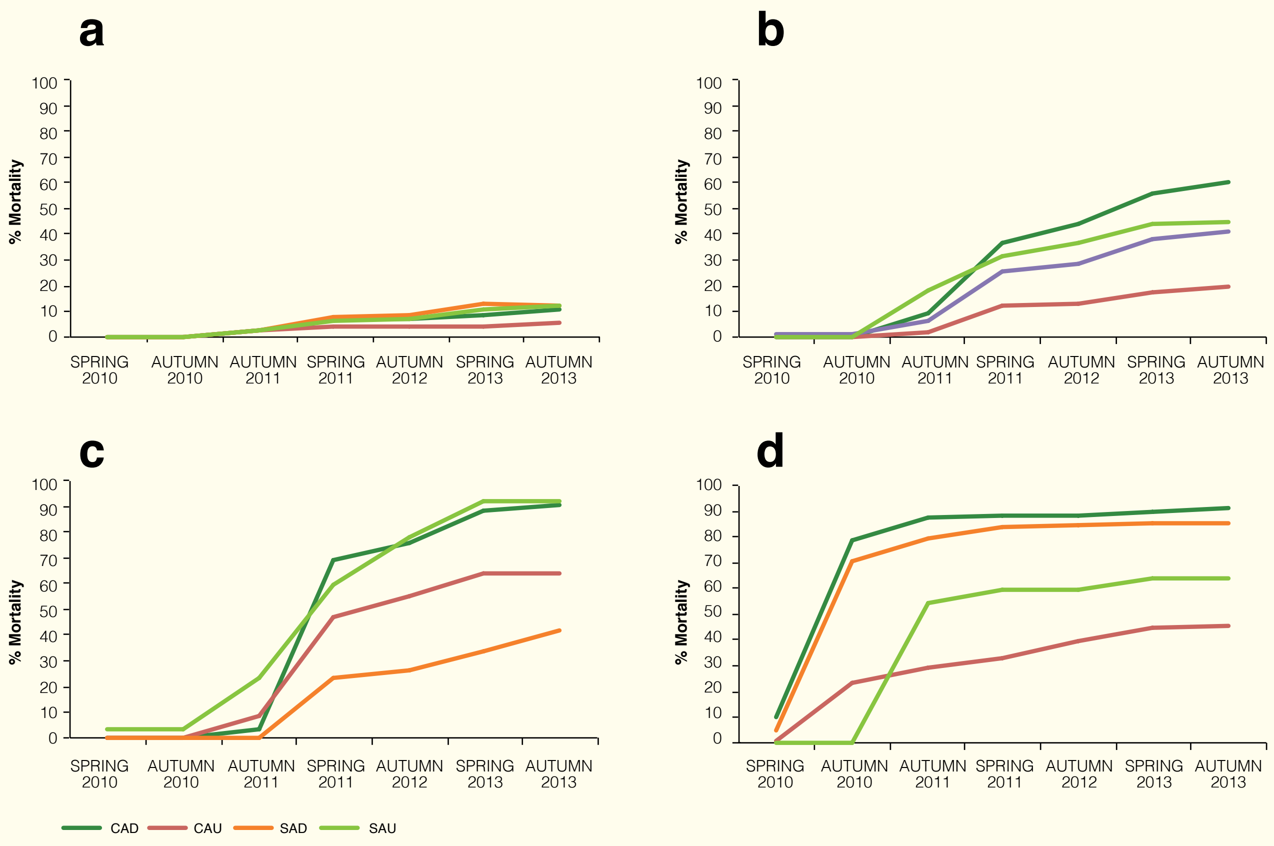
C. monogyna and *R. canina* were the species that showed the highest survival rate. The tree species that survived best were *P. pinaster* at low and *Q. ilex* at high elevations. In general, shrubby species adapted better than tree species did.

Table 1

SURVIVAL	With *Adenocarpus*	With *Ulex/Genista*	Without *Adenocarpus*	Without *Ulex*
Berberis hispanica	≈	+	+	-
Crataegus monogyna	-	+	+	-
Prunus ramburii	-	+	+	-
Rosa canina	≈	≈	≈	≈
Pinus sp.	≈	+	≈	-
Quercus ilex	-	+	+	-

Effect of pioneer shrubs (*Adenocarpus* and *Ulex/Genista*) on the survival rate of species introduced in the restoration. The positive and negative signs correspond to the higher and lower statistically significant percentages of survival, respectively.

Figure 1



Accumulated mortality rate of *Rosa canina* (a), *Crataegus monogyna* (b), *Quercus ilex* (c), and *Pinus sp.* (d) in the biennial monitoring conducted between spring 2010 and autumn 2013 with *Adenocarpus* (CAD), with *Ulex* (CAU), without *Adenocarpus* (SAD) and without *Ulex* (SAU).

Discussion and conclusions

A number of restoration actions have been designed to enhance vegetation diversity, both of species and structure, thereby improving the capacity to adapt to climatic change and extreme events. Perhaps the most novel of these actions has been the combination of different types of treatments according to the ecological characteristics and the history of management in the area. In order to promote natural regeneration, stands have been planted with irregular shape and different species composition. The stands have been combined with plantations by dispersal core areas, using a mixture of shrub and tree species. In every scenario, shrub species have shown better results than the trees have.

Specifically, the species that have shown the greatest percentage of survival rate have been wild rose (*R. canina*), hawthorn (*C. monogyna*), especially at low elevations. The barberry (*B. hispanica*) and Holm oak (*Q. ilex*) are the species that best responded at the high elevations. This diversity of responses to different ecological conditions is the basis for recovering a more resilient vegetation adapted to new climatic conditions.

The results for the experimental plots indicate that the burnt trunks and branches act as nurse structures, reducing soil temperatures and alleviating the water stress of the plants [7]. The burnt wood also acts as a major reservoir of nutrients that are gradually transferred to the soil [8]. Also, the structural complexity that the trunks and branches generate by being scattered over the ground protect the juvenile woody-plant species against ungulate herbivores. This translates as a higher recruitment rate and more vigorous growth of saplings, whether natural or planted [9]. On the other hand, the removal of wood also affects the ecosystem carbon balance [10] (see Chapter 7.1.). Soil respiration was greater in the presence of burnt woody remains, probably due to the greater microbial biomass and nutrient availability registered in the soil within this scenario [8]. Thus, wood cannot be considered the only option for post-fire management, whatever the characteristics of the area. There is an ample gradient of management possibilities for burnt wood, ranging from removal to non-intervention, which may include different degrees of removal, considering of different sensitivity to environmental factors (herbivory pressure, disease risk).

Aerial view of experimental plots one year after the fire (September 2006). The three plots without intervention can be distinguished (darker tone), three plots of 90% measuring and cutting up of the trunks, without removal (intermediate tone), and the traditional treatment (lightertone, similar to the rest of the area treated).

8.3. Population dynamics of the pine processionary moth: responses to climate changes and forest management

Hódar, J.A.[1]; Aspizua, R.[2]; Bollullos, C.[2] and Zamora, R.[1]

[1] Andalusian Institute for Earth System Research. University of Granada [2] Environment and Water Agency of Andalusia

Abstract

The data compiled in Andalusia indicate that the pine processionary moth (*Thaumetopoea pityocampa*) is spreading and intensifying the outbreak frequency over the last few decades. The pine forests of Sierra Nevada are situated at an elevation at which the processionary can be favoured by rises in temperatures. Therefore, we propose a prevention strategy based on the habitat management, planning the promotion of forest stands that are diverse both spatially and in species composition, making them more resilient to infestations and other forest-decay processes.

Aims and methodology

The pine processionary moth (*Thaumetopoea pityocampa*) exemplifies the way in which some defoliators of Spanish forests benefit from global warming [11]. The larvae of this species develop during the winter and therefore it can be expected that higher temperatures will have a positive effect, accelerating its development. To test this hypothesis, a demographic monitoring system was set up for the processionary in Sierra Nevada, to evaluate the hatching of caterpillars, their processions and burial, and the emergence of the moths. Three locations were chosen for sampling within the Sierra Nevada Protected Area, considering orientation, elevation, and dominant forest species. At each location, three sampling areas were established over the elevational range of the pines. The summer monitoring, from moth emergence to egg hatching (July-September), was conducted with pheromone traps for moths and surveillance of 30 egg masses at each elevation of the study area. The winter monitoring went from the time that the caterpillars leave trees (November-December) to the end of the burials (March-April). For this purpose, interception traps were set at the trunks of 30 trees per location, and the number of burials found in 1 km-long transects were recorded during each visit. The sampling frequency was 2-3 times weekly.

Results

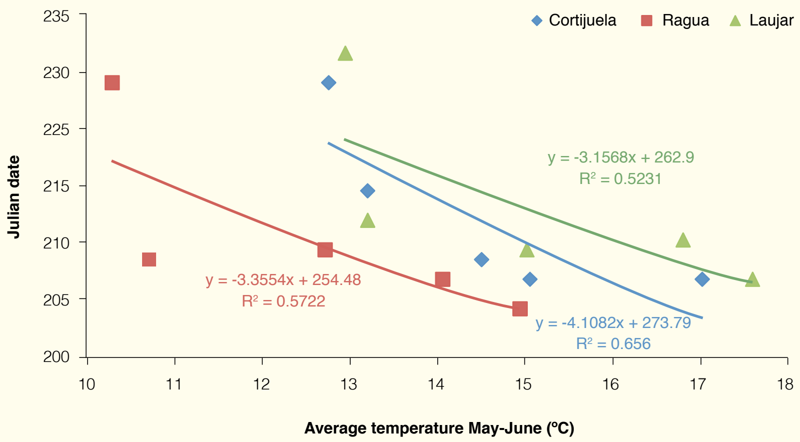
Although the defoliation by the pine processionary moth was visually alarming, the final effect on the attacked trees is limited, and the pines generally recovered well, so long as they did not suffer several defoliations in a row. The relationship between the defoliation by the processionary and temperature has long been known, in particular mild winters, so that in the context of global warming this species would be expected to colonize zones that, for latitude and elevation, have until now been free of this pest. These predictions have been confirmed in several studies [11-12]. In Sierra Nevada, the captures with pheromone traps show a clear relationship between the average temperatures of the previous spring and the median date of moth emergence in the season (Figure 1). A similar effect has been noted for the precipitation of the previous spring. In this sense, a reduction in spring precipitation, higher temperatures, or both, would encourage earlier emergence of the moths. Given that the temperature between the laying and hatching hardly varies, and that the recently hatched larvae are more sensitive to climatic conditions as well as to the quality of the food available, earlier hatching by several weeks would represent a considerable advantage for the larvae, which would then enter the winter in a more advanced state of development with presumably better conditions to survive. However, in part of its distribution area, the processionary follows five- to six-year infestation cycles, the length and duration of which appear to be regulated by biotic factors.

Thus, it is not clear that climate is the only factor explaining the population dynamics of this pest. Overall, a working hypothesis may be that a negative winter NAO (North Atlantic Oscillation), which in our region corresponds to mild, wet winters, triggers a population explosion of this insect, which wreaks maximum defoliation one or two winters later. After the peak, owing to the combined effect of colder winters, previously defoliated pines, and increased natural populations of parasitoids, the pest population returns to chronic levels.

Several predators can be postulated as being potential controllers of the processionary. In Sierra Nevada, the most common predators of the egg masses are bush crickets, which in some years and areas can consume more than half of the eggs. With respect to the parasitoids that attack the eggs, there is a clear pattern in the intensity of the parasitism: at higher altitudes, less parasitism. The percentage can vary from 50% of the parasitized eggs at low elevation to zero above 2000 m. a.s.l. (Figure 2). Apparently, while the processionary has managed to establish itself well at the highest elevations (finding a better relation between climatic variables and defoliation there [13]), this does not occur with its parasites, their control thus being limited at these elevations, where their activity is precisely most necessary.

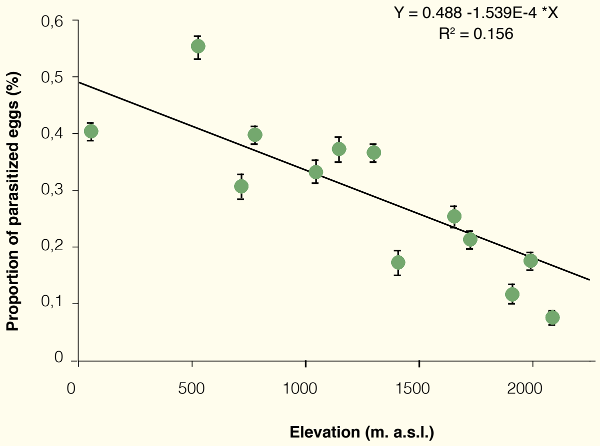
View of Trevenque and Trevenquillo climbing up to Collado Matasverdes, after the defoliation of 2010 (above) and 5 years afterwards (below). In the latter, although a new peak defoliation begins to be appreciated, the pines defoliated 5 years earlier clearly recuperate without problems.

Figure 1



Relationship between the median date of capture of the moths in pheromone traps in the study locations and the average temperature in the two months prior to the same spring, for the three locations monitored for the years 2009 to 2013.

Figure 2



Variation in the parasitism rate in egg masses of the processionary over an elevational gradient in the province of Granada. Each point (mean ± 1 standard error) represents the average rate of the plots at the same altitude and for four study years (2008-2011), totalling 1727 egg masses.

Discussion and conclusions

The main difficulty in identifying population trends in an organism such as the pine processionary moth is its cyclic dynamic. This species shows infestation episodes alternating with latency periods in which it is hardly detectable, a cycle that is completed in five or six years. The existence of other studies in the region with a longer series [12-13] help in the interpretation of the data from Sierra Nevada in a broader context. The analyses made indicate that the processionary clearly benefits from rising temperatures in the medium-high elevations of Sierra Nevada, since there the climate was until now the most limiting factor for this pest, natural predators are scarce at these altitudes, and it is also the area where most of the pines are found, natural or reforested. The management method used in Sierra Nevada is not focused on suppressing the pest outbreaks; treatments have only been applied in certain areas for public health reasons, either by tank or areal sprayers, or by manual control of the nests, with limited effectiveness, as confirmed in the studies made [14].

In the specific case of the processionary, it is known that mixing the pines with other species not susceptible to this pest (broadleaf species, for example) diminishes the intensity of the attack [15]. Diversifying the forest by adding other plant species also offers alternative resources (food and other hosts) to the parasitoids of the processionary, and introduces inappropriate habitats for the pupation of the larvae, reducing its populations. Also, other predators such as birds can be favoured by a suitable mosaic of habitats. It should be note that clearings opening implies a more conducive setting for the processionary, which prefers the edges of stands to develop. However, if the clearings are not bare but covered with thicket, the area becomes unsuitable for pupation and can make the processionary egg masses more vulnerable to predation by bush crickets.

In this sense, the lower density and diversification of the reforested pines are the general recommendations for future management of these forests. In forestry terms, this implies carrying out the necessary tasks to diversify the stands, promoting the mixture of the tree and shrub species as well as the spatial heterogeneity of the forest structure.

8.4. Naturalization of pine plantations

Aspizua, R.[1]; Bonet, F.J.[2] ; Zamora, R.[2] and López-Onieva, M.R.[1]

[1] Environment and Water Agency of Andalusia [2] Andalusian Institute for Earth System Research. University of Granada

Abstract

A large part of the 36,700 ha of existing pine plantations in Sierra Nevada are highly vulnerable to climate change. Therefore, a management priority is to increase their biodiversity, landscape heterogeneity as well as and functional performance. The studies made to date reflect the importance of the environmental variables (climate, altitude), landscape structure (fragmentation of the pine forest, size, density, position, and contact with the patches of native vegetation) and of past management in the composition, structure, and regeneration capacity of the reforested pine stands. Within the framework of the Sierra Nevada Global Change Observatory, the effectiveness of several types of treatments in different types of patches is being evaluated using a network of experimental plots. This monitoring results in recommendations for active management aimed at promoting the naturalization of the reforested sections over a broad range of environmental conditions, regulating competition, promoting mosaic structures of the vegetation, and preserving the individuals with high vegetative and reproductive potential. In reforested stands with intermediate density, diversifying the canopy and the structure by leaving dead wood, and fomenting the natural regeneration of woody species is recommended. Finally, in areas more than 2 kms away from patches of natural vegetation planting or sowing species adapted to the potential habitats according to current forecasts for climate change is proposed.

The largest extensions of reforested pines of Sierra Nevada appear in the Northern part of the mountain.

Aims and methodology

The aim of this work is to summarize the existing knowledge regarding the naturalization of the pine plantations in Sierra Nevada by collecting information from local experiences. For this purpose, some major aspects of the structure and regeneration capacity of the reforested pines (environmental variables, landscape structure, past management) are described. This is combined with an effectiveness assessment of different naturalization treatments applied in permanent monitoring plots distributed throughout the most representative pine forests on the massif [23].

Sierra Nevada Protected Area has more than 52,000 ha of dense tree formations, out of which 36,700 are reforested pines, planted mainly in the 1960s and 1970s over bare and eroded areas.

Although a large part of the pine forest surface area should have constituted a transition stage towards broadleaf formations or a mixture of broadleaf and pine species, the lack of forestry treatments has resulted in the practical stagnation of part of these masses. These are homogeneous, often monospecific, pine forests excessively dense. Trees in these forests have not been able to develop their crown or root system adequately due to excessive competition for water, light and nutrients. In many cases, there is no understory of woody species or it is very poor, in general of very low floristic and structural diversity. All this implies that these forests are under continuous physiological stress, which makes them highly susceptible to disturbances (drought, pests, etc.).

The strategy to improve their state (increase biodiversity, functional performance, resilience, etc.) is to reduce their density by selective thinning treatments.

One of the key issues to promote the naturalization of pine forests is to identify the most suitable places in which to apply the treatments. Another crucial aspect is to evaluate the results of the actions taken in order to know the impact that different treatments exert on the vegetation according to the previously defined objectives.

In this chapter, an analysis is made of the way in which regeneration and floristic diversity under the pine forest are influenced by biotic and abiotic gradients, the spatial configuration of the pine forest, and finally the past land uses. The results presented here are based on a forest inventory of almost 600 plots established in Sierra Nevada in 2004, on which many studies have been published ([16-17]; see Chapter 3.6), as well as on other specific samplings made by the authors.

Results

The analysis of different sources of information (the forest inventory made in 2004, the results from the analysis of these data published in scientific journals, and the laying out of experimental plots with their respective monitoring programmes) offer valuable information on the structure and functioning of the pine plantations. These results can be used according to the following structural and functional aspects:

Gradients of abiotic factors:

- Elevation and regeneration: the plantations located at low elevations (≈1300 m.a.s.l.) or moderate ones (≈1700 m.a.s.l.) showed a diverse and abundant recruitment bank dominated by species of the genus *Quercus*, while the highest plantations (≈2100 m.a.s.l.) had monospecific recruitment banks of Scots pine (*Pinus sylvestris*)[16].

View of a pine plantation before (left) and after (right) the naturalization treatments in Cortijuela (Monachil).

- Distance to the patches of Holm oak and regeneration of this oak under pine trees: An exponential decline in recruitment of the Holm oak was found when increasing the distance to the nearest Holm oak woodland, diminishing regeneration by 50% beyond 250 m, and up to 80% beyond 1 km (see Figure 1).

Pine-forest structure and land uses:

- Density of the pine forest: regeneration was null at densities above 1,500 pines/ha, while moderate densities (500-1,000 pines/ha) showed better regeneration, both of the pines as well as of other species, in comparison with open tree canopies. Only the Aleppo pine (*Pinus halepensis*) registered the highest regeneration rates at very low densities (0-100 pines/ ha), while the greatest regeneration of Holm oak occurred at 1,100 to 1,300 pines/ha, this being consistent with the need for shade of this species in its early growth stages [16].
- Pine patches size and floristic diversity: greater floristic diversity was observed as the size of the pine patch diminished [17].
- Type of vegetation adjacent to the reforested pines: the higher the percentage of contact with natural vegetation, the more abundant were the birds that disperse pine seeds as well as seeds of zoochorous plants in their interior [18].
- Past land use: the probability of finding Holm oak regeneration on the ground is inversely proportional to the intensity of the management of land use in the past, being progressively greater in pastures, crops, mid-mountain shrublands, and *Quercus* forests (see chapter 3.6).

› Discussion and conclusions

The varied ecological gradients of the Mediterranean mountain enormously determine the regeneration dynamics of pine plantations. This forest type should be considered (and managed) as dynamic systems where the successional paths and diversity levels are determined by abiotic factors, complex balances of competition and facilitation, the spatial configuration of natural seed sources, and the characteristics and needs of each species [16].

The studies made in Sierra Nevada demonstrate that the naturalization of pine plantations depends both on the history of the stand (which determine the legacy of prior land use) as well as the current ecological characteristics. For the study of the effect of these biotic and abiotic gradients in the response of the masses to the different treatments, a network of permanent plots were monitored in Sierra Nevada. This enables the assessment of the most effective actions in each type of vegetation mass within a few years, considering the history of its prior use and its current ecological context to achieve the established aims.

Given the results described, a series of management recommendations are included here to promote the naturalization of reforested areas similar to those studied in Sierra Nevada:

I. Very dense pine plantations (>1,500 trees/ha): regulate competition at the same time as allowing the entry of light, seeds and dispersal agents. For this:

- Different intensities thinning treatments to foster the fragmentation of pine plantations. In addition to varying the number of trees to be cut in the different copses, thinning from above can be applied (cutting trunks of larger diameters) in some places to favour latter natural perturbations and appearance of thickets. This should be done with the precaution not to encourage excessive heliophilous colonizing thickets, which would imply regressive successional dynamics and raise the fire risk.
- Leave the senescent, fallen, and dry individuals as well as those that show high vegetative and reproductive rate.

II. Middle density pine plantations (500-1,000 trees/ha): apply treatments for the diversification of the canopy to encourage mixed, irregular forests, adjusting the intensity of the thinning to the ecological conditions of the stand. For this:

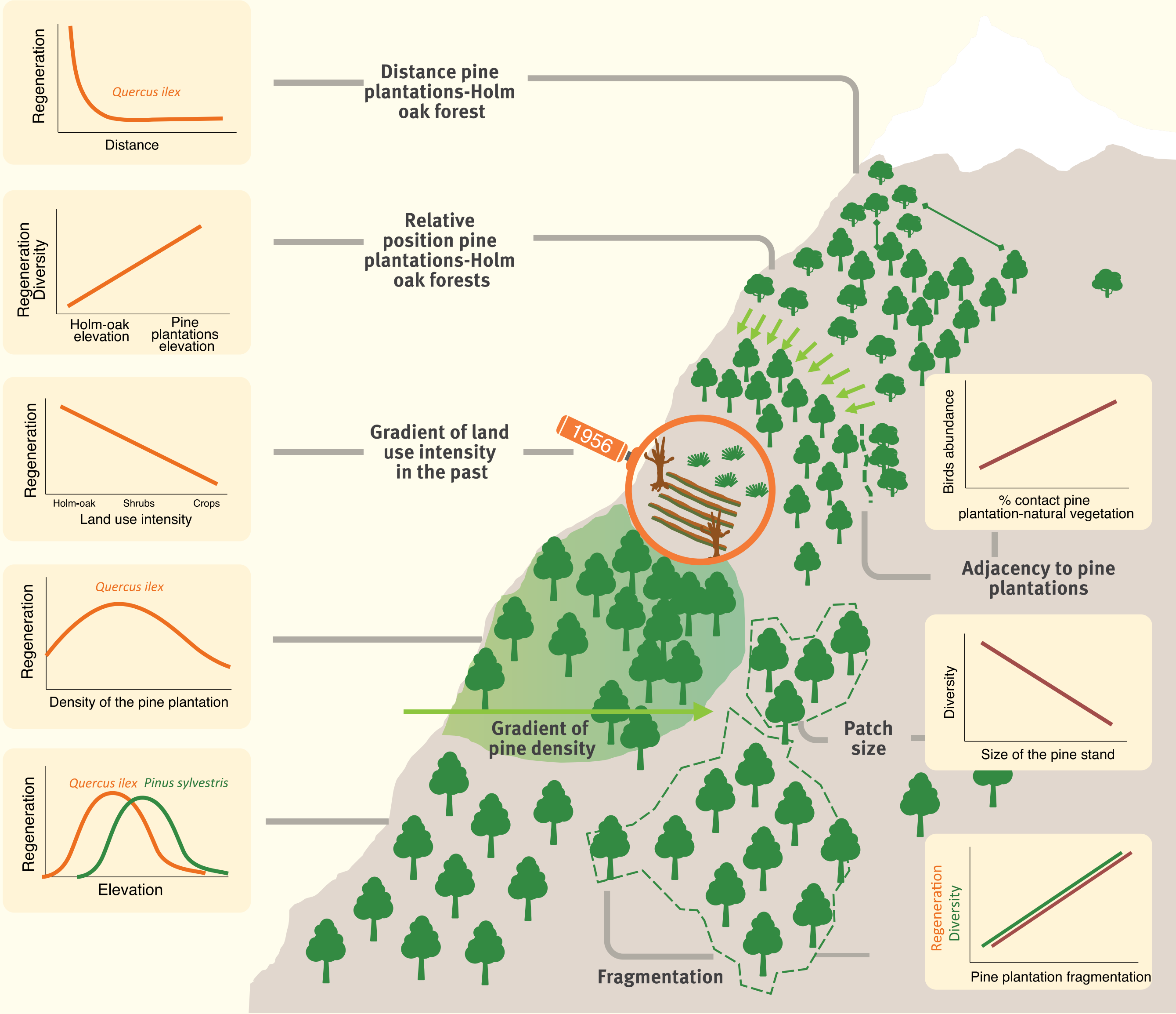
- Favour natural regeneration by the thinning of copses.
- Where regeneration of umbrofilous species is present, open the canopy proportionally to the size of the established recruits.
- Obtaining large size trees from a selection of the dominant ones and opening of space around them (some 100-150 trees/ha, of which some 50 would be kept without pruning) [19].

III. Leave dead wood (maximum of 5% of the trees) as recommended in different studies [19].

IV. Maximize the contact surface area between the plantation and natural vegetation, whether trees or shrubs, as this has demonstrated to have a positive influence on zoochorous dispersal [18].

V. Where natural recruitment is deemed very slow due to excessive distance to the natural sources of seeds or intensive use of the land in the past, it will be necessary to reinforce the populations by enrinchment seedling or planting. For this purpose, the species adapted to the potential habitats should be used according to the predictions of climatic change.

Figure 1



Schematic summary of the main results found in relation to the naturalization of reforested pines. The scheme shows the role of abiotic factors (elevation) and biotic ones (pine density, fragmentation, and size of the stands, relative position of the patches providing the acorns, source-sink distance, adjacency of natural vegetation to the pine stands and the effect of past land use).

8.5. Impact of global change in the Pyrenean oak forests of Sierra Nevada: recommendations for management

Bonet, F.J.[1] ; Pérez-Luque, A.J.[1] ; Aspizua, R.[2] ; Muñoz, J. M.[2] ; Zamora, R.[1]

[1]Andalusian Institute for Earth System Research. University of Granada [2] Environment and Water Agency of Andalusia

Abstract

The Pyrenean oak forests (*Quercus pyrenaica*) in Sierra Nevada stand at the limit of their natural distribution. For their survival, they require wet summers, which are not frequent in the southern Iberian Peninsula. Furthermore, they have undergone a history of intense management in recent centuries (charcoal making, felling, pruning, abandonment of traditional uses, etc.). Finally, they are also affected by climate change. This situation has driven the Pyrenean oak forests of Sierra Nevada to the limit of their self-maintenance capacity, compromising their expansion to suitable adjacent areas (abandoned croplands and pine plantations). The studies made to date reflect the importance of the elevational gradients in the functioning of the Pyrenean oak forest. Those situated at low elevations of the north-eastern area produce fewer acorns than those to the south do. Also, the capacity of the Pyrenean oak forest to recolonize pine plantations and croplands has been evaluated. The results indicate that the location is important also in this case: regeneration appears to be more intense under the pines of the northern area, while in the south there are more recruits invading abandoned croplands. These results should be taken into account in forest management.

Aims and methodology

The aim of the present work is to compile the main evidence of the impact of global change on the structure and functioning of the *Quercus pyrenaica* forests of Sierra Nevada. In addition, recommendations are provided for management based on this evidence.

The oak forests of Sierra Nevada show a high degree of singularity in terms of species composition. Three homogeneous clusters have been identified according to their environmental conditions and their species composition (Figure 1a). In this sense, major differences are found in the functioning and structure of the oak forests on the northern and southern sides of the massif.

On the other hand, this forest type has been intensely perturbed over its history, fundamentally by the cutting of wood in the low parts of the mountain and, less frequently, its conversion to meadows for pasturing. This has overwhelmingly determined their current distribution, occupying 3,500 ha in Sierra Nevada [25]. These forests show a notable lack of vegetative vigour, poor acorn production, and a predominance of asexual reproduction. This situation has been attributed to the exhaustion of the strains, although recent studies have demonstrated considerable genetic diversity [21]. The high water requirements of this oak in summer make it a vulnerable species in a global change scenario. Simulations of climate change predict a significant contraction in its potential habitat [22]. Therefore, it is vital to develop management procedures for these forests based on the best scientific evidence available. This way, the most adequate forest structure for generational turnover will be achieved.

In this sense, both the current legal framework as well as the management regulations of the Sierra Nevada Protected Area establish two basic aims for the management of these forests:

1. To improve these structure and functioning of the oak forests. This aim is related to the problems caused by human activity intervening intensely within the *Quercus pyrenaica* forests (thinning, charcoal production, etc.).
2. To improve the capacity of expansion into potentially habitable sites. This means to promote the recolonization of abandoned crops or pine plantations and possible elevational shift.

The methodology followed in this work is based on the analysis of different sources of data compiled or generated by the Sierra Nevada Global Change Observatory since 2009 to 2016. Most of the data were taken in stands that represent three oak forests previously identified. Table 1 shows these sources of information.

Table 1

Name	Project to which it belongs	Variables of interest to this work	Temporal range
Assessment of the pine plantations management	Monitoring Programme of Global Change in Sierra Nevada	• Reforested pines diversity • Oak regeneration after different pine thinning intensities	2011-2015
Flowering phenology of oak forests		• Initial flower production • Successful flower set • Acorn production	
Monitoring of the bird dispersers		• Abundance of bird dispersers	1989, 2009-2015
Monitoring of ungulate populations (Spanish ibex and wild boar)		• Density of individuals	1960-2015
Monitoring of plant communities: Native forests and shrublands of the medium and high mountain		• Species diversity and richness	2011-2014
Colonization of croplands and altitudinal migration	MIGRAME (Global Change, Altitudinal Range Shift and Colonization of Degraded Habitats in Mediterranean Mountains; Excellence Research project funded by Andalusian Government)	• Spatial distribution and abundance of recruits in abandoned crops, at the limit of the forest and in reforested stands. • Characterization of the structure (age categories of the recruits) and evaluation of herbivore damage. • Behaviour and abundance of bird dispersers • Historical reconstruction of the Pyrenean oak forest distribution in Sierra Nevada.	2011-2016
Characterization of damage to broadleaf forests by defoliators in Sierra Nevada	Monitoring of forest damage in the Spanish network of National Parks (National Park Service)	• Incidence of the defoliator complex in Pyrenean oak populations in Sierra Nevada	1992-2015

Summary of information sources in this chapter.

Results

The analysis of the existing information enables the identification of a number of problems involved in the functioning and structure of the *Quercus pyrenaica* forests in Sierra Nevada.

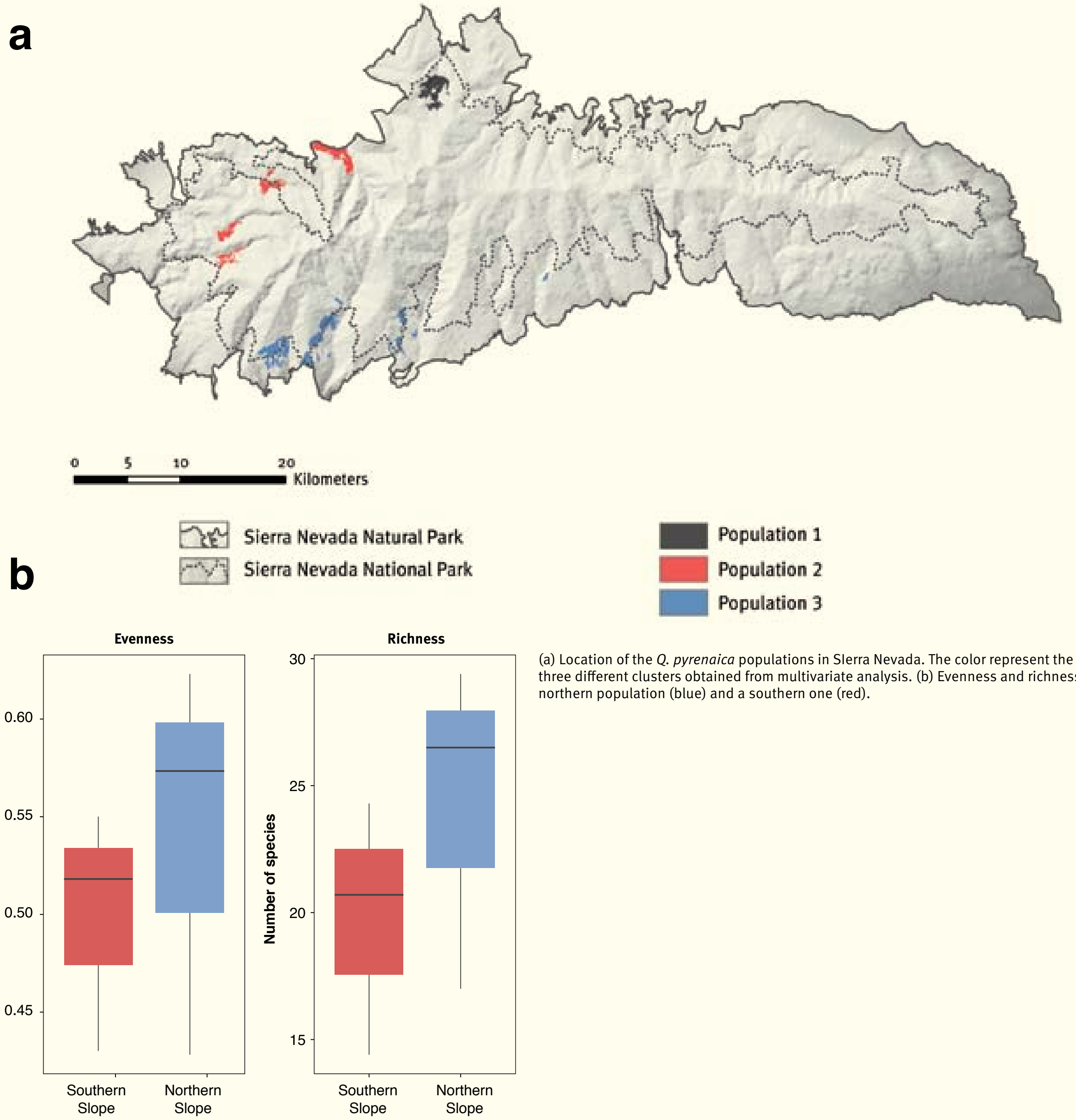
Regeneration problems of the oak forest

The monitoring of female flowers production reveals differences in production among the different populations (higher in the south than in the north). In addition, differences were also found between the high and low elevations in all the populations, being significantly lower at low elevations. On the other hand, the final acorn yield showed a similar pattern, with differences between populations (higher in the north). Also, the acorn-production values were greater at high elevations than at lower ones.

In recent decades, the abundance of Eurasian jay (*Garrulus glandarius*: the main dispersers of acorns for this oak) has decreased. In the last 30 years, the density of this bird has fallen from 6.6 ind/10 ha in the 1980s to 1.25 ind/10 ha at present (see chapter 5.4) [24]. The main cause of this change may be the densification of the oak forests observed in the last few decades as a consequence of the abandonment of mountain crops. On the other hand, the densities of the jay showed no significant differences between populations of the north-east and those of the south (data for 2007-2013).

In addition to the limitations in flower and acorn production, the Pyrenean oak populations undergo considerable mortality among seedlings and juveniles in Sierra Nevada, due primarily to summer

Figure 1



(a) Location of the *Q. pyrenaica* populations in Sierra Nevada. The color represent the three different clusters obtained from multivariate analysis. (b) Evenness and richness of a northern population (blue) and a southern one (red).

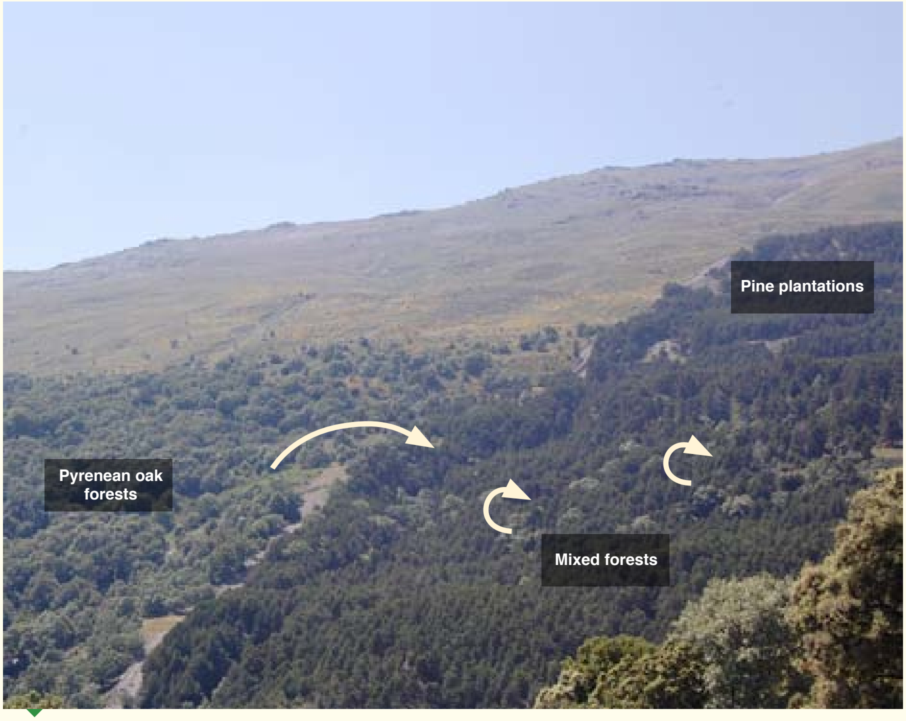
drought and ungulate herbivory. Finally, a scattered increase has been detected in some years in the incidence of the defoliator complex of *Quercus* in Sierra Nevada. This increase in defoliation could affect acorn production.

Limitations on oak-forest expansion

The limitations indicated above reduce the expansion capacity of the oak forests. Studies have been made to evaluate the capacity of these oak forests to colonize both the adjacent reforested pines as well as the abandoned croplands. The high density of pine plantations in Sierra Nevada hamper their colonization by the oak. In 2011-2012 experimental treatments were made to evaluate the facilitator effect of pine thinning of different intensities on oak-forest regeneration (see chapter 8.4).

The dynamics of the oak forest is too slow to show a clear effect on regeneration under the pines in two years. However, greater regeneration was in fact detected in the north-eastern populations (2.75 ± 0.29 ind/25 m^2) than in the southern ones (1.24 ± 0.19 ind/25 m^2). In addition, it seems that the intensity of the treatment had different consequences depending on the orientation of the oak stand. In this sense, plantations surrounding the north-eastern populations showed greater diversity than those of the south.

On the other hand, the abandonment of the traditional crops over the last 50 years provide more areas for the oak forests to colonize. The natural difficulties for this to occur augment due to summer drought and overgrazing in many areas. This process of recolonization of the abandoned croplands is expressed in a different way depending on the type of oak forest. In Cáñar (south) recruitment proved greater than in San Juan (north).



The oak recruitment in the pine plantations also depends on the dispersion distance from native forest. In this photo we show a native forest patch acting as a source of oak propagules for an adjacent pine plantation.

Discussion and conclusions

The distribution of the oak forests of Sierra Nevada and their degree of conservation are determined both by biophysical variables that are expressed at present (orientation, climate, water availability etc.), and by the dynamics of land-use changes in recent decades (intensive use and subsequent abandonment). In addition, climatic change also determines the functioning of these forests. The combination of these factors explains the current situation of the oak forests in Sierra Nevada. The results show that flower and acorn production differ between the northern (less) and the southern (more) populations. Also, differences were observed in the sexual reproduction capacity between elevations, being stronger at higher elevations and vice versa. On the other hand, the capacity of the oak forest to expand is also determined by orientation. The preliminary results showed that oak forests regenerated more readily on the north-east than on the south slopes. Finally, the colonization of the 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 location).

The differences indicated above reflect a differential response of oak forests both to climatic factors (which change along altitudinal and geographical gradients) as well as against the two different types of land use (which vary from place to place at a local scale). The low elevations seem to be more severely affected by the drier and warmer climate, showing a scenario that could occur in the higher elevations in the coming decades. In addition, the differences found in the functioning of the various population orientations reflect the ecological plasticity of these forest systems against the combination of biophysical and land-use variables.
Other preliminary results show changes in the functioning of the ecosystem that do not seem to be related to orientation or elevation. The densification process of these forests after the abandonment of traditional uses (see chapter 3.3), the decline in the Eurasian jay populations or the increase in the incidence of defoliating pests are examples of these changes.

This situation shows the key problems of sexual regeneration and of expansion that the oak forests of Sierra Nevada face at present, problems that should be addressed by the design of adaptive management measures.

Considering these results, a number of recommendations are provided for managers:

Actions to improve the sexual-reproduction capacity of the oak forest:

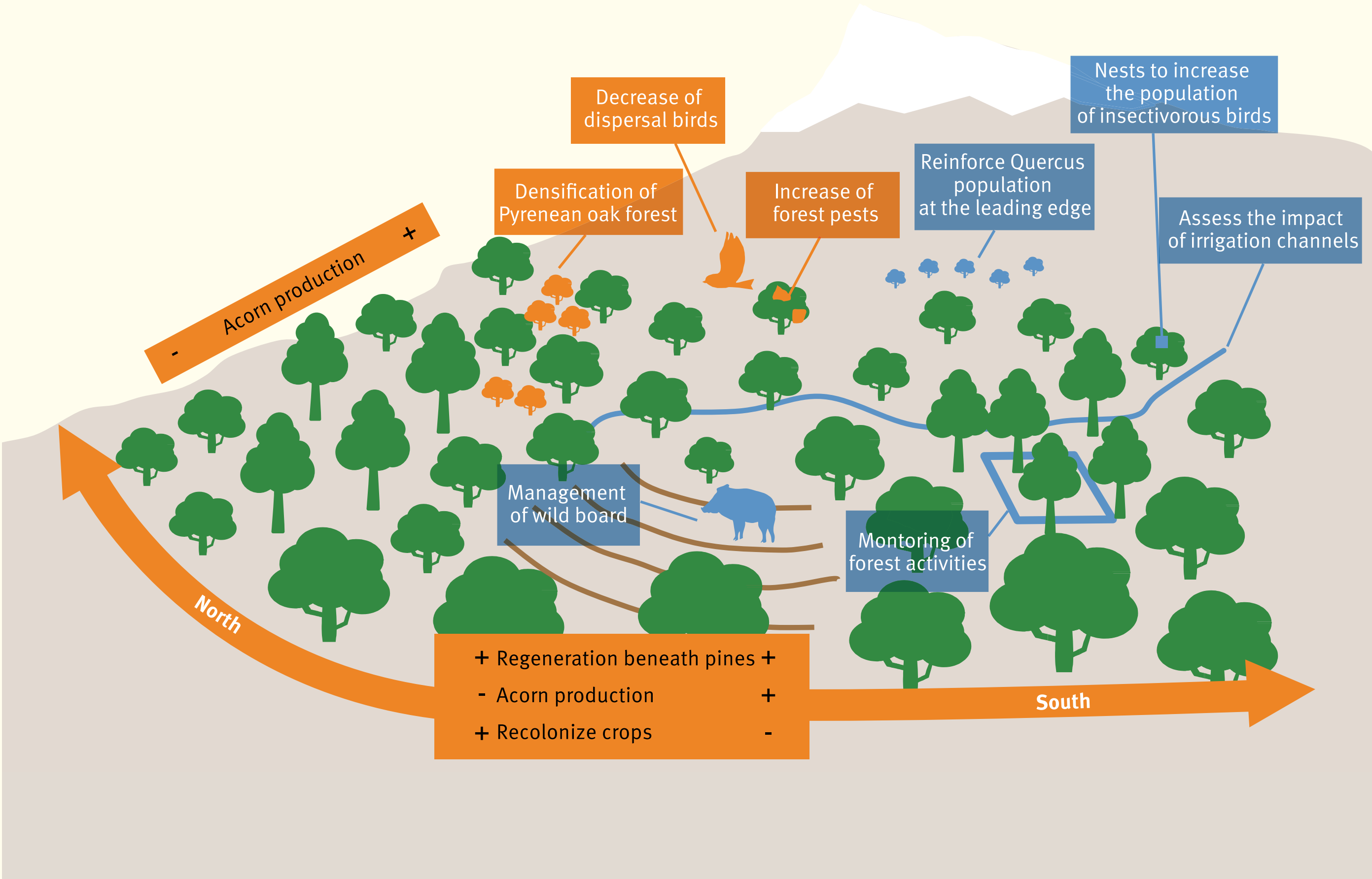
- Instalation of nest boxes to minimise the impact of defoliators. Insectivorous birds exert a major force in controlling populations of defoliating insects. The installation of nest boxes could help curb the impact of these pests in the oak forest.

- Maintenance of the management plan of the wild boar. This has succeeded in stabilizing populations of this ungulate. This will have a positive effect on the recruitment rate in these oak forests.
- Evaluation of the effect of traditional irrigation channels on the oak forests. These channels are potentially useful to help the oaks overcome dry summers in Sierra Nevada, since they moisten the soil. Their role will become more crucial in view of the predictions for climate change.

Actions to improve the expansion capacity of the oak forest:

- Characterization of the population of dispersing species. Dispersal and establishment in suitable habitats are key limiting factors for the expansion of these oak forests. For this purpose it is fundamental to know the state of the populations of Eurasian jay and of rodents, which are the main acorn dispersers.
- Reforestation in suitable places according to the forecasts for climate change. These forecasts indicate that this species will ascend elevationally in the future. To contribute to this process, reforestation is proposed at the upper limit of the existing oak populations. In this way, the advancing front of this species will be reinforced.
- Maintenance of the monitoring of forestry actions in pine plantations adjacent to the oak forests. It is important to improve the existing knowledge regarding the colonization and establishment of oaks in pine plantations. For this, it is necessary to continue monitoring the experimental thinning undertaken in the pine plantations.

Figure 2



Scheme showing the main impact of global change on Pyrenean oak forests of Sierra Nevada (orange), as well as a number of management proposals for this ecosystem (blue).

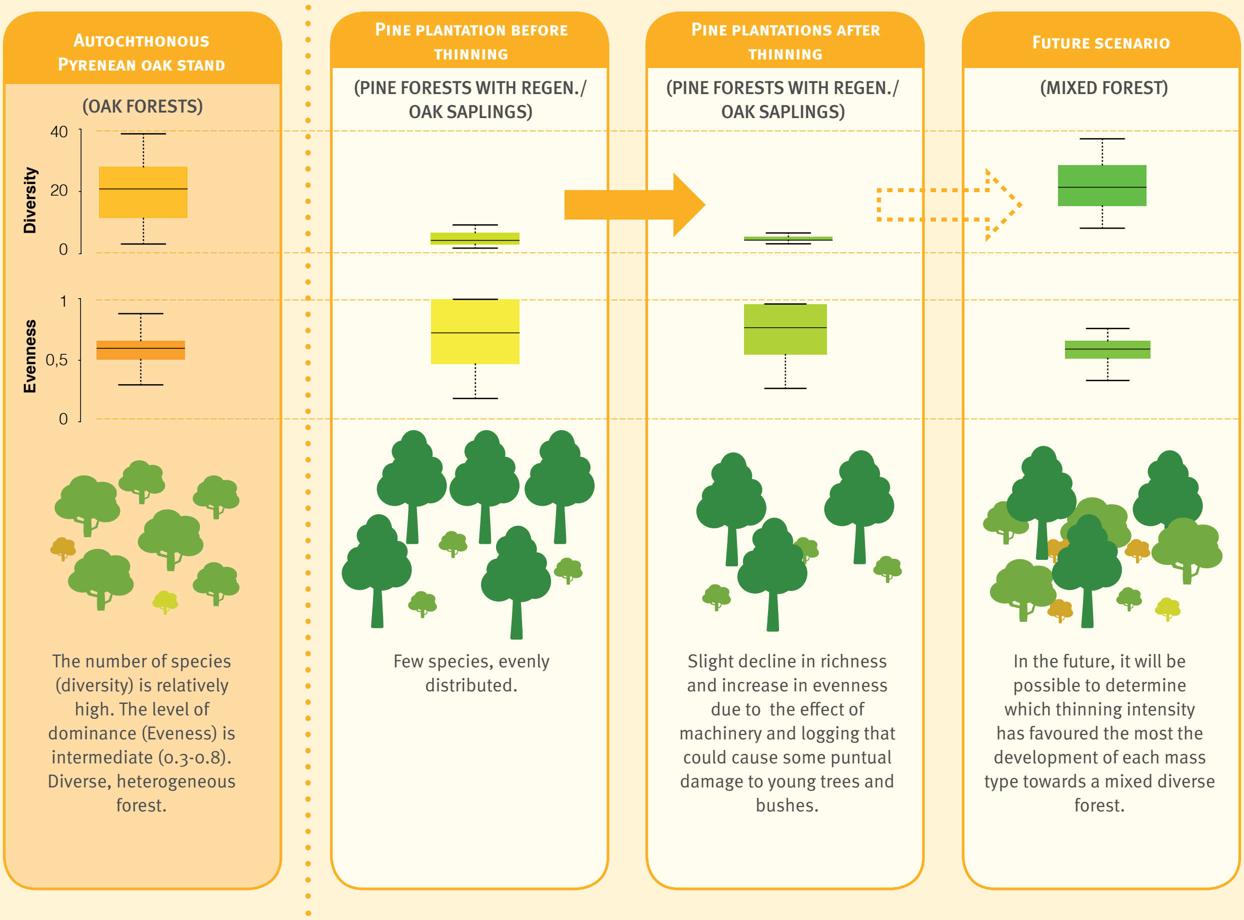
Assessment of the management of mixed *Pinus* and Pyrenean oak forests to promote resilience.

In an effort to facilitate the expansion of the oak forests of Sierra Nevada and in search of a dynamic and resilient forest model, a number of actions have been undertaken in Scots pine (*Pinus sylvestris*) plantations close to oak (*Quercus pyrenaica*). Density reduction of the pine plantation enables the development of oaks and other woody species, both trees and shrubs. This increases floristic, structural, and finally functional diversity of the ecosystem.

To assess this management activities, the Sierra Nevada Global Change Monitoring Programme has established plots where, two circumstances coincide: (1) the existence of a relatively dense Scots pine forest with abundant regeneration or oak saplings and (2) the proximity of an oak forest that functions as a seed source.

At each location, several treatments (different thinning levels) have been established. This experimental design has been used to study the regeneration or recolonization of tree and shrub species as well as the presence of grass species. The inventories are made immediately before the forest action and repeated a year afterwards. The methodological details can be found elsewhere [23].

The monitoring has shown the development of the forest from the different treatments applied. As time passes, the repetition of inventories will make possible to characterize the actions that have contributed the most to achieve the aims laid out starting from the initial situation in each type of stand.



Simplified comparison by box diagrams of the diversity of species measured through two components: species richness (number of species in the community) and the evenness (similarity in the relative abundance of species). The value 1 of evenness indicates a uniform distribution of individuals.

Specimen of Pyrenean oak (*Quercus pyrenaica*) in Camarate (Lugros, Granada province).

8.6. Analysis of susceptibility to slope instability in Sierra Nevada

Azañón Hernández, J.M. and Pérez-Peña, J.V.
University of Granada

Abstract

In this study we have analyzed several climatic, topographic and geological variables in order to evaluate landslide susceptibility in the Sierra Nevada National Park. We analyzed separately three different typologies of slope instabilities; namely landslides, fluxes and rockfalls. Apart from the typical variables such as those related to topography, geology, and land use, we incorporated other ones that had not previously been evaluated. These variables are the normalized vegetation index (NDVI), the snow-cycles and the duration of snow, and the runoff threshold (P0). We made a multivariate statistical analysis to get the variables that better explain the variance distributions of each movement typology. The weights of the selected variables in the susceptibility map of the three different landslides typologies were obtained by a statistical discriminant analysis. From the three new analyzed variables, the NDVI showed the greatest relevance. The increase in torrentiality associated with climate change generates a greater number of superficial landslides and rockslides. These superficial processes can be exacerbated by changes in land use and produce losses in the vegetation cover. Torrential winter precipitation can reactivate large dormant landslides.

The image shows the northern face of Mulhacen Peak and La Mosca Lake.

Aims and methodology

Slope movements or landslides, whether natural or induced, constitute geological risks that have to be considered and take into account in territorial planning. The losses of materials associated with landslides can incur very high costs, thus justifying the importance of preventive studies. In this study we propose a methodology to analyze landslide susceptibility in the Sierra Nevada National Park.

Most studies on landslide susceptibility include only variables extracted from the Digital Elevation Mode (DEM), and other ones related to geology and/or land use. Nevertheless, in this study we have included some external variables directly related to climate. Some of these variables have been never analyzed in previous landslide susceptibility studies in the region, such as the normalized vegetation index (NDVI), the thaw cycles and the duration of snow, and the surface-runoff threshold (P0). This study differentiates three different typologies of slope movements; landslides, flows and rockfalls. We have compiled a movement inventory for each typology by using photointerpretation and subsequent field validation. We evaluated susceptibility for each movement typology by performing a multivariate statistical analysis in order to identify those variables that better explain the variance distribution of each slope movement typology. To do so, we applied a principal component analysis (PCA). The different weights for the selected variables were extracted by a discriminant analysis, and used to draw different susceptibility zoning maps for each movement types. Finally, we derived a final map by combining the information of the three susceptibility maps.

Results

Of the three new climatic variables analyzed, the number of snow- cycles and the number of days that the snow remained on the ground had the least weight, although their incidence in the generation of surface landslides was important.

The normalized difference vegetation index (NDVI), derived from red and near-infrared spectral channels from a LandSat TM satellite image (July, 2010) was critical in the three types of movement. This index reflects the state of the vegetation at the time the image is captured. Therefore, in future studies it would be very interesting to analyze variations of this index over time. These variations could have a strong influence on the susceptibility to slope movements.

The land type and land use were evaluated together through the runoff threshold variable. This factor has a different importance in the three types of movements, with higher impact in landslide movements and lesser in flow and rockfalls. These results reinforce the idea that susceptibility studies should examine the different slope instabilities separately, as the factors that influence such typologies will not have the same weight. Once the different susceptibility maps have been derived for each movement typology, they have been combined in the general susceptibility map of Figure 1.

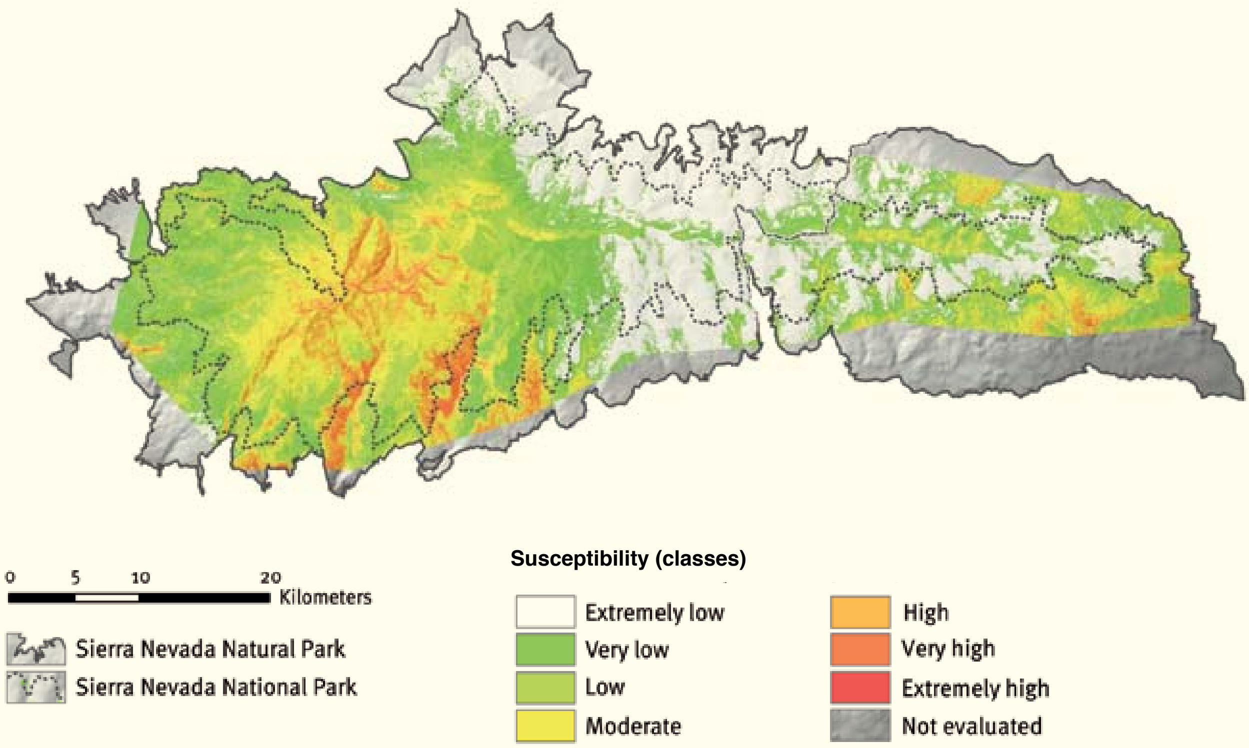
Rotational landslide in the Lanjarón River valley.

› Discussion and conclusions

The main instabilities concentrate in the western part of Sierra Nevada (Figure 1), where the analyzed climate variables have more weight. Nevertheless, it is also true that the surface and tectonic processes developed over the last million years are more active in this sector. In this western sector, which has the highest elevations, the slopes are steeper and the rate of incision of the drainage network is higher. The present-day fluvial network has re-excavated an older glacier morphology conditioning topography and generating steep valleys with high local slopes in their sides.

Regarding the consequences of climatic change, the uncertainty over the future increase in the frequency of torrential precipitations and abnormally wet climatic episodes does not permit conclusive statements. High torrentiality will increase the frequency of landslides and rockfalls. The repercussion of these higher frequencies can be exacerbated by changes in land use and shrinkage in the vegetation cover. This will need to be taken into account in future planning actions, especially in the sectors where our analysis showed higher slope instability. In these areas, future actions have to maintain or increase the vegetation cover in order to minimize soil losses.

Figure 1



Susceptibility map of slope instability in the Sierra Nevada National and Natural Park.

Durcal River valley and Caballo summit in the background.

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› Más referencias en http://refbase.iecolab.es/ref_dossier_resultados.html”

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Chapter 9

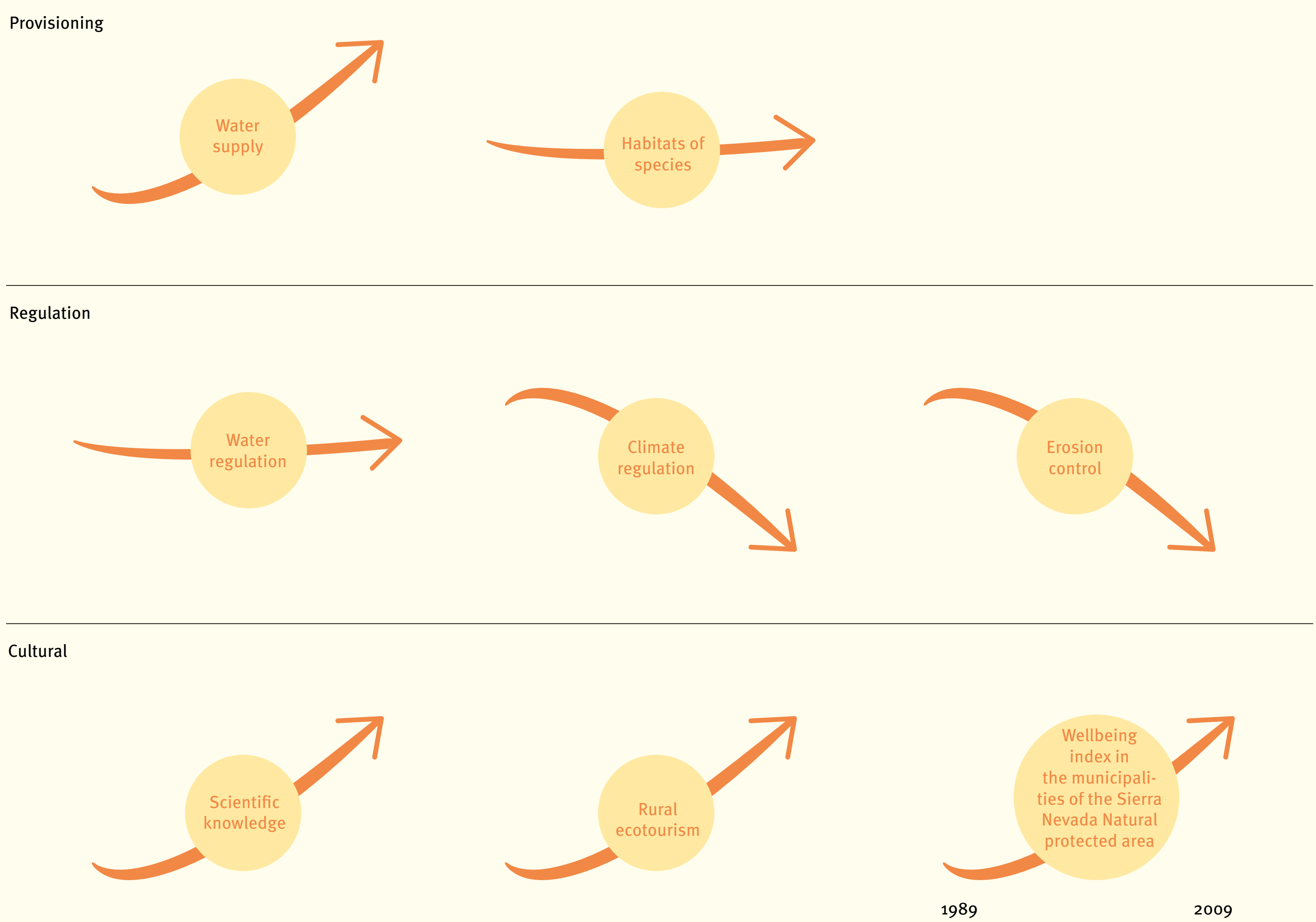
View of Sierra Nevada

Socioeconomy and ecosystem services

In the last 50 years, humanity has altered ecosystems in the most intense way of any other period in history, in large part to satisfy growing demands of food, water, wood, fibres, and fuel. The result has been a substantial alteration of the functioning of the ecosystems of the entire planet, a phenomenon known as global change.

Ecosystems offer services to society: provisioning (food, water, natural resources), regulation (flood control, water purification, air purification) and cultural services (aesthetics, education, recreation).

The management of natural capital demands a consistent and global administration of territory, as the processes that determine the functioning and function of the ecosystems extends beyond the administrative limits of protected areas. It requires commitment to diverse policies such as hydrological planning, tourism, agrarian policies, and the conservation of biodiversity, among other things, in the context of territorial planning. Within the emerging process of global change, the protected areas confront numerous challenges, notably changes in land use of its surroundings and the lack of support of the local populations for the use restrictions imposed. Today the problems of conservation in protected areas, whether terrestrial or marine, are



Graphic summary of the main results presented in this chapter. All the graphs except the last one are based on the perception of the people included in the poll. The last graph shows the objective results based on real data. All the graphs reflect trends of change from the past to the future.

primarily beyond the limits of that area and are fundamentally socioeconomics.

In the present chapter, two examples show the importance of natural protected areas from a socioeconomic point of view. On the one hand, protected natural areas, apart from acting as instruments for the conservation of biodiversity and ecological processes, contribute in an essential way to the protection of the capacity of their ecosystem to generate services. On the other hand, by the analysis of different socioeconomic indicators, it is shown that the wellbeing of municipalities belonging to protected areas has increased in recent years.

Therefore, from the socioeconomic perspective, the protected areas act as generators of ecosystem services that are offer benefits both within the protected space as well as outside of it, favouring the wellbeing of human populations living within the protected areas.

9.1. Temporal evolution and distribution of ecosystem services of Sierra Nevada

Palomo, I.[1,2]; Martín-López, B.[2] and Montes, C.[2]
[1] Basque Centre for Climate Change [2] Autonomous University of Madrid

Abstract

Evaluations of ecosystem services for environmental management have been increasing considerably in recent years. However, there are hardly any applications to the management of protected areas. Therefore, a participative workshop was organized with managers and researchers associated with the Sierra Nevada National Park, in order to evaluate the perceptions of the participants on the time evolution of the ecosystem services and their spatial distribution (including the supply and demand of services). The results show that certain ecosystem services such as the control of erosion or the aesthetic values are diminishing, while others, such as eco-tourism, rural tourism and scientific knowledge are increasing. The services are generated primarily by the protected ecosystems of the Sierra Nevada, especially the summit areas, while most of the beneficiaries of these services live outside the limits of the National Park, in Granada and other nearby populations.

› Aims and methodology

The creation of protected areas is one of the main strategies to conserve nature [1,5]. Several international initiatives have highlighted the importance of considering the ecosystem services in conservation, emphasizing the Millennium Ecosystem Assessment (MA), The Economics of Ecosystems and Biodiversity (TEEB), and the Intergovernmental Panel on Biodiversity and Ecosystem Services (IPBES). In this work, a preliminary approach to the inclusion of ecosystem services in the management of the Sierra Nevada Protected Area (SNPA) is presented. Protected area managers, environmental decision-makers as well as researchers of the Universities of Granada and Almería participated in this research. These participants selected the most important ecosystem services in the SNPA, as well as their evolution in the last few decades to the present. Afterwards they mapped the Service Provision Hotspots (SPHs), the SPHs in decline, and the beneficiaries of the services. The maps were photographed by an SLr digital camera and were imported and analysed by a geographic information system (ArcGIS 9.2).

› Results

The most important services considered, their trends, and the scales of their beneficiaries are detailed in Table 1. The services associated with water are considered key in the SNPA, as well as the habitats for species. On the other hand, erosion control, climate regulation, aesthetic values, and food from extensive agriculture should be considered priority services due to their regressive tendency. Finally, it can be appreciated that the scale at which these services are received span the local to the global scale.

Table 1

Ecosystem service	Relative importance of the service (%)	Trend	Scale of beneficiaries
Water provision	27	↑	Regional-local
Habitat for species	17	↔	Global-regional-local
Hydrological regulation	17	↔	Regional-local
Eco-tourism	7	↑	Global-regional-local
Rural tourism	7	↑	Global-regional-local
Climate regulation	6	↓	Global-regional-local
Air quality	5	↔	Global-regional-local
Erosion control	4	↓	Regional-local
Scientific knowledge	4	↑	Global-regional-local
Ski tourism	4	↔	Regional-local
Aesthetic values	2	↓	Global-regional-local
Food from non-intensive farming	1	↓	Local

Ecosystem services generated by the SNPA that are most important for the wellbeing of humans according to the participants of the workshop, relative importance of these services with respect to the total services selected, trend perceived, and scale of the beneficiaries.

The participative mapping of the ecosystem services has resulted in the maps in Figure 1. The ecosystems included within the limit of the national park appear as the main suppliers of ecosystem services, highlighting the high summits for the importance of the services associated with water. The SPHs perceived in decline coincide mainly with the ski resort of Pradollano (Figure 1 B). The beneficiaries of the services live mainly in the metropolitan area of Granada and Almería.

Discussion and conclusions

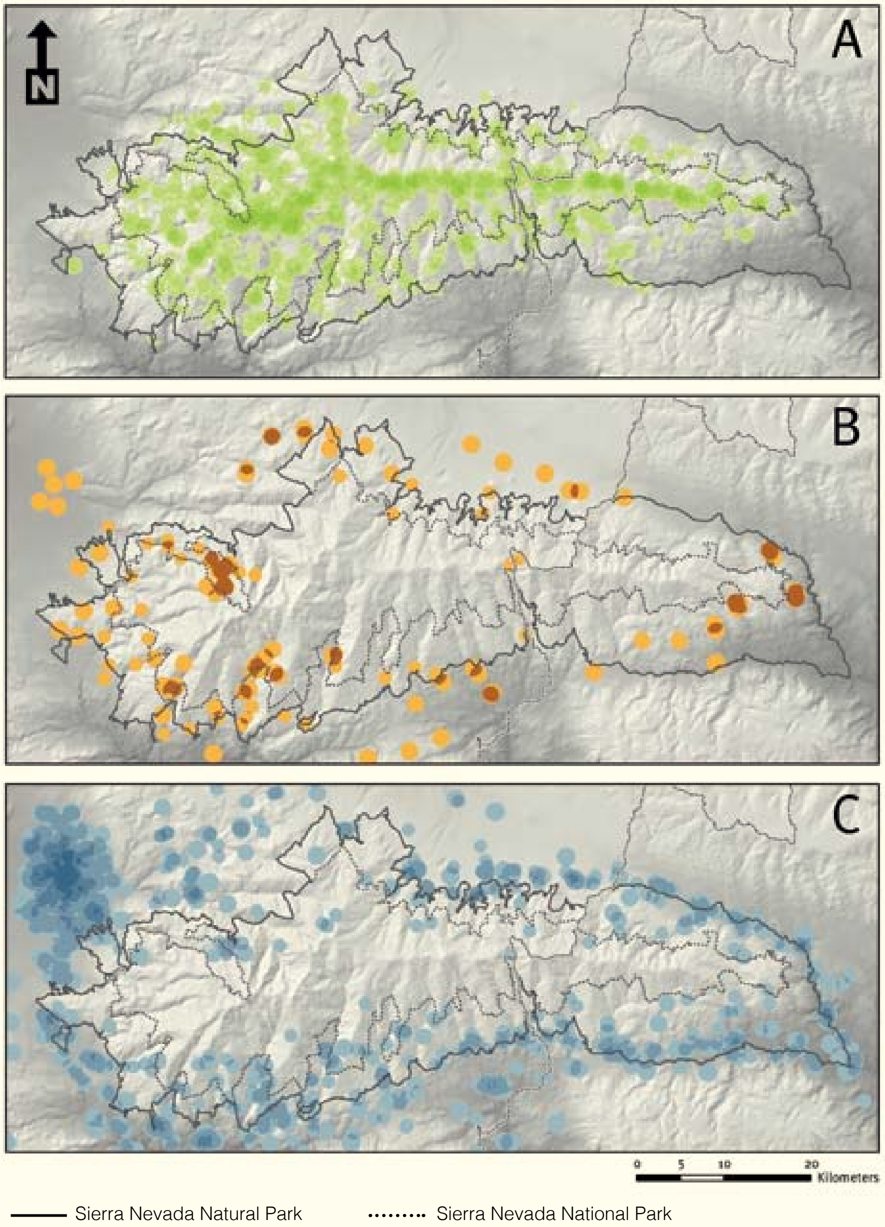
The present work constitutes a preliminary approach to the management of protected areas under the framework of ecosystem services [4]. The inclusion of ecosystem services reconnects humans and nature by the explicit recognition of intrinsic values [2]. Specifically, for protected areas, this strategy seeks to strengthen social support for these spaces, on showing the multiple services provided.

The results show that certain ecosystem services are in regression, some (e.g. climate regulation or the loss of aesthetic value) are due to global change. The results indicate furthermore that the SNPA should be managed on multiple spatial scales, given that beneficiaries of those services pertain to local, regional, and global scales. This scalar uncoupling between the supply and demand for services has been shown in other studies with services associated with the forests of Sierra Nevada [3].

The mapping of services has enabled the identification of specific areas for management. For example, the area of Güejar Sierra annex of the national park (which has not been declared a natural park) should be considered a priority zone for management since it delivers multiple services and is not protected. Pradollano appears as an example of an area with services in decline and thus could be considered a priority zone for restoration.

The character of the study undertaken, by the participation of researchers and managers, has made it possible to outline a new theoretic framework and methodology for managing the SNPA. This is relevant, given the calls from international organizations such as the International Union for Nature Conservation or the European Union to introduce ecosystem services into the management of protected areas. Furthermore, participation permits bringing closer research and management.

Figure 1



Spatial distribution of the Service Provision Hotspots (SPHs) (A: green), the SPHs in decline (B: red) and the beneficiaries of the services (C: blue) according to the perceptions of the participants.

9.2. Temporal analysis of wellbeing in the municipalities of Sierra Nevada

Pérez-Luque, A.J.; Moreno-Llorca, R. A.; Pérez-Pérez, R. and Bonet, F.J.
Andalusian Institute for Earth System Research. University of Granada

Abstract

Wellbeing in municipalities of the Sierra Nevada Protected Area Space has been characterized. For this, information was compiled from 22 socioeconomic indicators belonging to 8 dimensions of wellbeing. A diachronic analysis was performed between two temporal points: in 1989 (before the declaration of the natural protected area) and 2009. The results show that the wellbeing has increased in the municipalities of the Sierra Nevada Protected Area between 1989 and 2009. Comparisons with other studies reveal that the improvement in wellbeing is greater in municipalities belonging to protected areas.

Aims and methodology

To analyse wellbeing in the municipalities of the Sierra Nevada Protected Area, the approach used was based on compound weighted indices [6]. The synthetic index of wellbeing, DP_2, which combines different simple indicators that characterize wellbeing, was used [7]. This indicator enables comparisons between spatial and temporal entities and has been broadly used in the measurement of wellbeing at different scales [8]. For this, the information from 22 socioeconomic indicators representing different dimensions of wellbeing were used (Table 1). This information comes from the compilation of socioeconomic information from several sources, which has been integrated into the information system of the Sierra Nevada Global Change Observatory (https://linaria.obsnev.es). For each municipality, the DP2 index was calculated in 1989 and 2009, using a free software algorithm [10]. For each municipality, a well-being ratio (WR) was computed as the ratio between the well-being in 2009 and well-being in 1989. A value of WR greater than 1 indicates well-being improvement whereas a value less than 1 indicates worsening over the time period considered.

Table 1

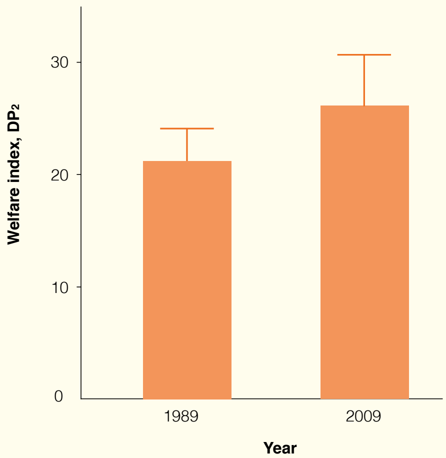
Dimensions	Indicators
Population	Births Population growth Interior emigration Interior immigration Ageing index
Health	Healthcares centres
Employment	Employed population Unemployed population
Economy and income	Business activities Personal income Buses Lorries Vans Cars
Infrastructures	Hotels Phones lines
Education	Schools Elementary teachers
Culture and leisure	Public libraries Restaurants
Social participation	Voter turnout

Indicators used in calculating the wellbeing of each municipalities.
The dimension of wellbeing to which each belongs is indicated.

Results

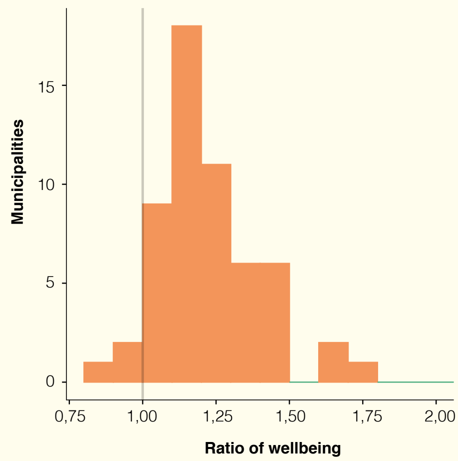
For the municipalities of the Sierra Nevada Protected Area, a significant increase in wellbeing was noted between 1989 and 2009 (Figure 1). Of the 56 municipalities for which data are available, a decline in the wellbeing index was found in only 3 municipalities (values of the wellbeing ratio below 1). On the other hand, no relation was found between the increase in wellbeing and the percentage of belonging to a municipality in a protected area.

Figure 1



Synthetic indicator of wellbeing DP2 (mean ± standard error) for the municipalities of the Sierra Nevada Protected Area between 1989 and 2009.

Figure 2



Histogram of the number of municipalities against the ratio of wellbeing.

Discussion and conclusions

The data for the increase in wellbeing between 1989 and 2009 found for the municipalities of the Sierra Nevada Protected Area agree with those found for all of Andalusia for this period [9]. The results at a regional scale indicate that the municipalities belonging to the natural park presented a greater increase in wellbeing between 1989 and 2009 than did those outside the park.

Our results stress the importance of protected areas, not only from the standpoint of conservation of biodiversity, but as generators of ecosystem services that are beneficial to society for their socioeconomic relevance.

Hikers trekking to “Lavaderos de la Reina”

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9.1. Temporal evolution and distribution of ecosystem services of Sierra Nevada

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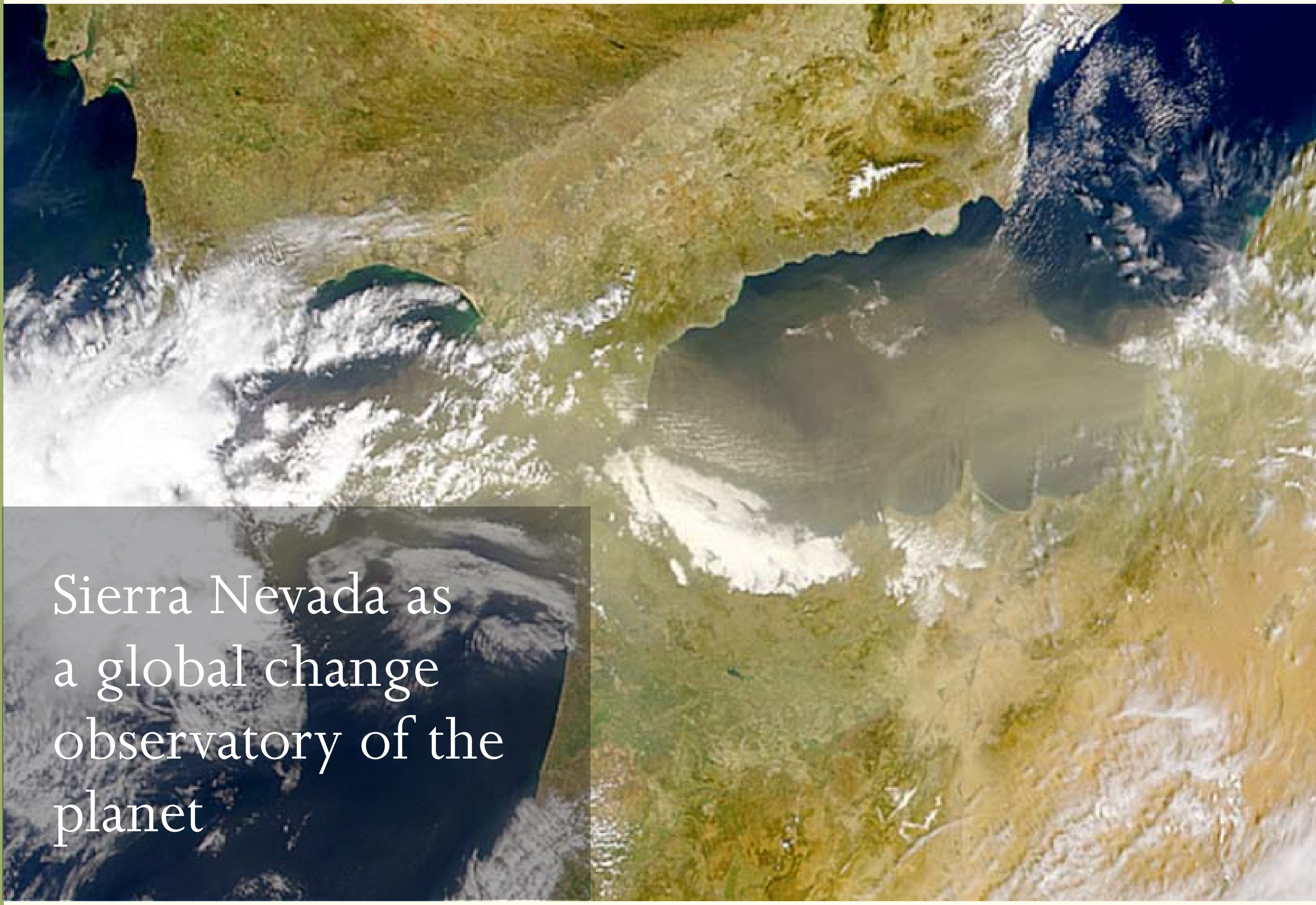
Chapter 10

Cloud of Saharan dust over the Alboran Sea. Image taken by the SeaWIFS sensor of NASA 23 March 1999



Sierra Nevada as a global change observatory of the planet

Mountain ranges offer extraordinary oportunities to conduct research and to monitor global change, since they can be used as observatories for remote processes. Two types of processes cause changes at a broad scale. On the one hand, those processes that have acquired a planetary dimension by aggregation of local impacts (such as habitat fragmentation and land-use changes). On the other hand, regardless of their origin, those human impacts whose effects are propagated at the planet scale through fluid layers enveloping the Earth: oceanic and continental waters, and especially the atmosphere. This second class includes processes considered more genuinely global and are precisely the processes that can be observed better from the mountains, as exceptional lookouts. In this sense, mountains 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. The electromagnetic radiation emitted by the lightning of storms that is occurring worldwide, particularly in the tropical belt, is being monitored in Sierra Nevada. This radiation is especially intense in extremely low-frequency ranges (ELF band), and is transmitted around the world throughout the atmospheric layer existing between the earth and the ionosphere that acts as a waveguide. The ELF-measurement station of *Juan Antonio Morente*, situated on the Loma del Mulhacén

Schumann resonance

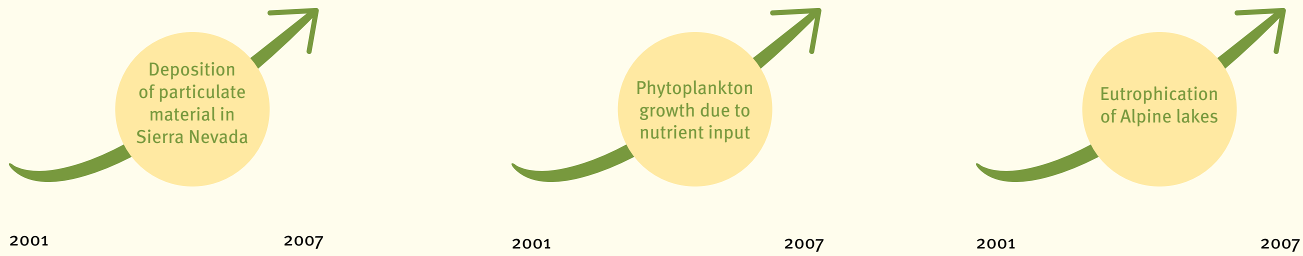
is a good indicator of the Earth's temperature

SO2 and NO2 concentrations

are higher in Granada than in Sierra Nevada

Aerosol generation

is increasing worldwide



Graphical summary of the main results described in this chapter. Time evolution of the biophysical variables from 2001 to 2007.

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at 2500 m.a.s.l., serves as a valuable tool for a global-scale monitoring from Sierra Nevada of the main storm areas of the planet. This station measures Schumann resonance, which acts as a global thermometer of the Earth and can provide data on global climate change.

Mountains are also very sensitive to environmental changes because of the fragile equilibrium in the components of the natural system, and thus, these ecosystems can be used as sensors to detect early signs of change. For example, high-mountain ecosystems are important sensors of global pollution because their isolation from human activity make them receptors, paradoxically, of industrial pollution that circulates through the atmosphere worldwide. Toxic elements, from metals to pesticides, which circulate through the atmosphere are deposited in mountain ecosystems, entering into trophic chains and biogeochemical cycles.

The atmospheric transport of materials is highly efficient, implying that regional emissions can be transported long distances reaching other regions of the planet. This has been clearly observed in studies performed on high mountain lakes of Sierra Nevada, where the influence of different vectors of global change on communities, especially the increased aerosol load, has been. The generation of atmospheric aerosols is a growing phenomenon at the global scale, which transports and disperses nutrients, pollutants, and microorganisms thousands of kilometres away. Changes in atmospheric circulation have increased the arrival of Saharan dust, which increases the atmospheric deposition of phosphorus in lakes. This has caused the growth of phytoplankton, causing changes in the configuration of the of the trophic networks and the biogeochemical equilibrium of lakes. This is also a clear example of how human impact reaches remote places and demonstrates the need to consider the impact of global change on ecosystems from an integrated perspective.

10.1. The monitoring of worldwide storm activity with the Juan Antonio Morente ELF station of Sierra Nevada

Salinas-Extremera, A.; Fornieles-Callejón, J. and Portí-Durán, J.
University of Granada

Abstract

From Sierra Nevada, the electromagnetic radiation emitted by lightning during storms worldwide is being monitored. This radiation is especially intense at the extremely low frequencies (ELF) band and is transmitted troughout the world by the layer between the Earth and the ionosphere that acts as a waveguide. The intensity of the signal transmitted has peaks at frequencies known as Schumann resonances. These act as a global sensor of the Earth and can provide data on global climate change.

Aims and methodology

The terrestrial atmosphere comprises several layers with very different physical characteristics. From the electromagnetic standpoint, its structure can be simplified in two layers: (*i*) the ionosphere, situated from 100 km in height and characterised by high conductivity, and (*ii*) the gas layer that goes from the surface of the Earth to the ionosphere, characterised electromagnetically by practically null conductivity. Most of the natural electrodynamic phenomena occur in this layer, storms (lightning) being their main expression.

The electromagnetic field produced by lightning is propagated through the atmosphere. The signal within the kilohertz band (those frequencies that can be picked up by a radio near the storm in the form of clicks) is attenuated a few kilometres from where the lightning occurred. However, part of the low frequency (ELF band) can be propagated throughout the Earth, continually bouncing between the ionosphere to the Earth's surface. For this part of the electromagnetic field produced by lightning, the atmosphere acts as an immense cavity delimited by the Earth's surface and the ionosphere [1]. This signal, known as Schumann Resonances (SR), is measured at the station located in Sierra Nevada [2].

This is the only station in Spain that measures SR. The station has two magnetometers: NS (sensor 0) and EW (sensor 1) oriented. The signal measured by each sensor is digitalized at a sampling frequency of 256 Hz. Figures 2 and 3 show the results of a discrete Fourier Transform with a window averaging 30 seconds an hour. Results are calibrated from a frequency of 0 to 25 Hz.The maximum amplitudes and the corresponding frequencies are derived from the averaged signal. The first three modes of SR are detected within the calibration range of the station. The station also enables the detection of variations in the fourth mode.

Results

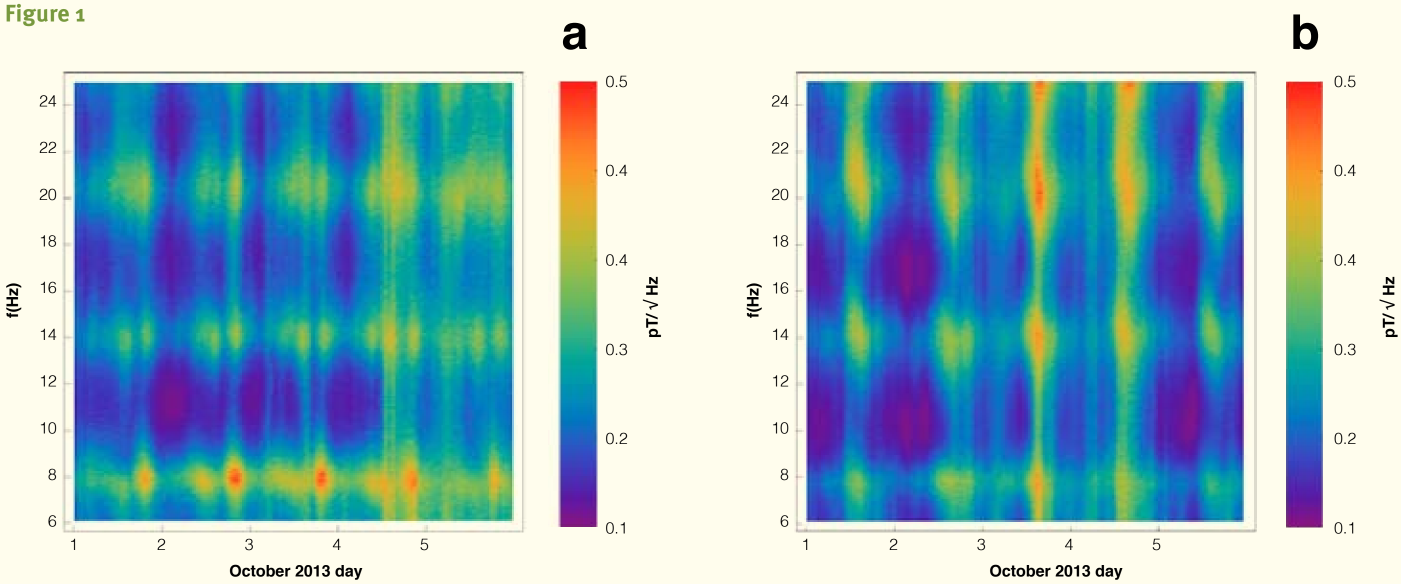
The ELF station has been working without interruption (except for maintenance tasks) since July 2012 [4]. Figures 1 and 2 show some of the results obtained with the processing of measurements collected during this period.

Figure 1 shows the spectrogram of the signal in the frequency band of 6 to 25 Hz for the first 5 days of October 2013. Frequency is shown on the vertical axis, and the signal amplitude for each frequency is represented in a colour code by the scale at the right. Each plot corresponds to a sensor. The first three modes of the SR correspond to the frequencies of 8, 14, and 21 Hz. These resonances can be detected more clearly during days of low electrical activity, such as days 1 and 2, while the spectrum becomes flatter on days with high electrical activity, such as day 4, indicating that the storm activity source is closer. The variations in the resonance frequency of each mode enables the estimation of the distance between the observer (station) and the storm centres, thereby allowing the study of their annual drift.

Figure 2 shows the daily time course by seasonal periods of the amplitude of the first resonance from March 2013 to February 2014, measured by both sensors. It can be noticed that the amplitude increases during summer (boreal) as opposed to winter (boreal). Also, the sensor 0 shows the storm-activity peaks at approximately 12 UT and 20 UT, whereas sensor 1 presents amplitude peaks (in the first mode) during sunrise and very significantly at around 15 UT, corresponding to the activation of the storm centre of Africa.

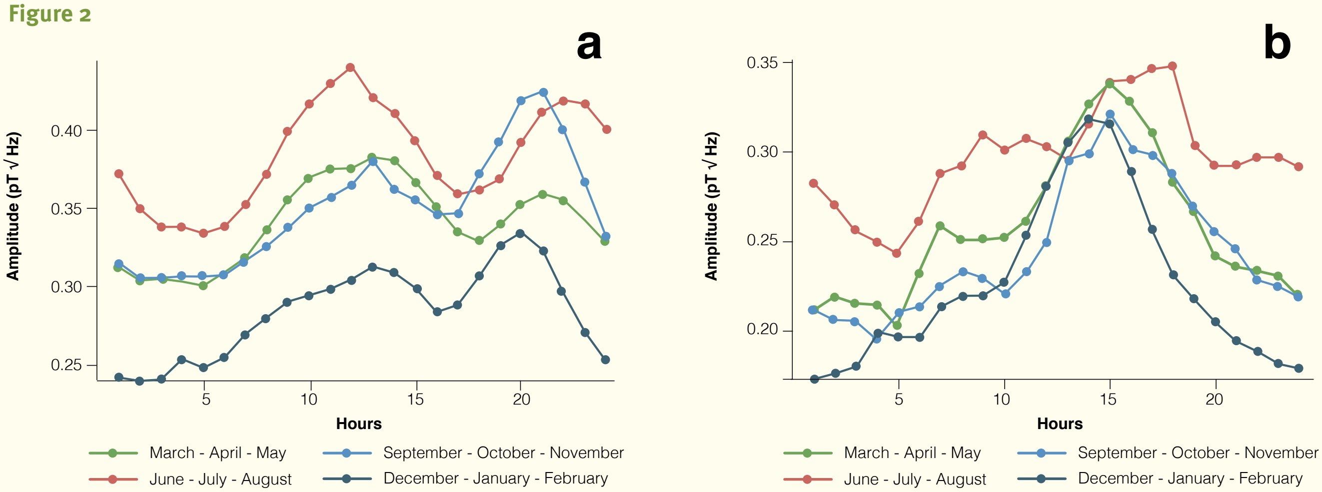
Currently, the analysis of data from the station continues. Also, efforts are being made to contact other research teams that have ELF stations or other types of observatories of natural electromagnetic noise in order to compare measurements.

Figure 1



Spectrogram of the signal measured by the sensor 0, left, and sensor 1, right, during the first 5 days of October 2013.

Figure 2



Daily evolution of first resonance amplitude in different seasons, measured by sensor 0 (left) and sensor 1 (right). Measurements collected from March 2013 to February 2014.

Discussion and conclusions

The ELF *Juan Antonio Morente* measurement station constitutes a valuable tool for worldwide monitoring of the main storm centres of the planet from Sierra Nevada. SR act as an Earth's thermometer and can provide data about global change. The link between SR and tropical temperature of the atmosphere was established through the number of lightning bolts per second that, on average, are being produced in the world [3]. Therefore, the measurement of the SR can be considered an indicator of overall Earth temperature, and its monitoring through time could provide information on global change. It is important to note that the measurement of SR in Sierra Nevada comes not only from the electromagnetic field generated by lightning activity produced by nearby storms but also from the global Earth's storm activity. The SR presents daily, seasonal and annual variations, which can be detected through measurements made with the station. The drift of the fundamental nuclei of storm activity towards the south in the warmest years, when El Niño phenomenon occurs, or towards the north in the coldest years, when La Niña occurs, influences the measurements of the SR, and therefore it is possible to monitor the phenomenon at planetary scale by taking measurements far away from the areas directly affected.

These data also contribute to the study of the effect of solar storms and seismic precursors on the ionosphere through statistical variations of the resonance frequencies and irregular increases in the amplitude at frequencies of tenths of a hertz. In this sense, the variations measured in SR through multiple stations distributed at different points of the Earth could serve to predict earthquakes with a lead time of days or weeks.

View of the monitoring station.

10.2. Monitoring of atmospheric pollutans

Muñoz, J. M.
Environment and Water Agency of Andalusia

Abstract

The monitoring results of SO_2, O_3, and NO_2 concentrations in Sierra Nevada are presented in comparison with data from the urban station of the city of Granada (Granada-Norte) available on EIONET. For the data collected in Sierra Nevada, a downward trend for NH_3, O_3 and SO_2 was detected, whereas a stabilization of NO2 was observed. Great differences are measured in NO_2 and SO_2 between Granada and Sierra Nevada. Following the concentration modelling of each contaminant, a projection was made. In general, although with the available data it is difficult to make a reliable prediction over the long term, the concentration of contaminants will foreseeably continue within the detected trend.

Aims and methodology

In the light of potential negative effects of certain pollutants on natural ecosystems, a protocol has been put into practice to monitor air quality in Sierra Nevada.

The concentrations of four atmospheric pollutants were recorded from 2008 to 2013 at three different points by passive dosimeters. Previous data are available for the period 2001-2004 as well as data on the concentrations of three pollutants at a station in the city of Granada (accesible at: www.eionet.europa.eu). Prior to the analysis, the series were homogenised. The collector was replaced every 14 and 15 days for the period 2001-2004 and 2008-2013 respectively. The station in Granada city registered the concentration measurements every hour.

After the data homogenisation, the averages of the concentrations in the city of Granada were calculated for the same time interval in which the collectors were installed in Sierra Nevada.

When the two data series (2001-2004 and 2008-2013) were defined, several analysis methods were used: linear regression, simple smoothing, double smoothing, Stl (*Seasonal and Trend decomposition using Loess*), Holt-Winters smoothing, and ARIMA. All these techniques are available in TSA packages [5], tseries [6], and forecast [7] of the statistical program R.

Results

The comparative analysis of the distribution of the concentrations (Figure 2) shows high concentrations of sulphur dioxide (SO_2) and nitrogen dioxide (NO_2) in the city of Granada in relation to any point in Sierra Nevada, while the concentrations of ozone (O_3) show an inverse pattern, with minimal differences between the city and Sierra Nevada. The European normative considers ozone concentrations higher than 40 ppb (parts per billion) to be harmful to plants, this known as the AOT index [8-9].

Ammonia (NH_3) concentrations are similar in the three points analysed in Sierra Nevada (Figure 2). This gas is related to primary human activities (livestock and agriculture). There are no data available for this gas in the city of Granada.

The difference between the two series (Figure 3) indicates some temporal changes. In general, the concentrations decreased but the relative differencesamong measuring points remain. Concretely, NO_2 concentration slightly increased in the city of Granada, but did not significantly change in Sierra Nevada.

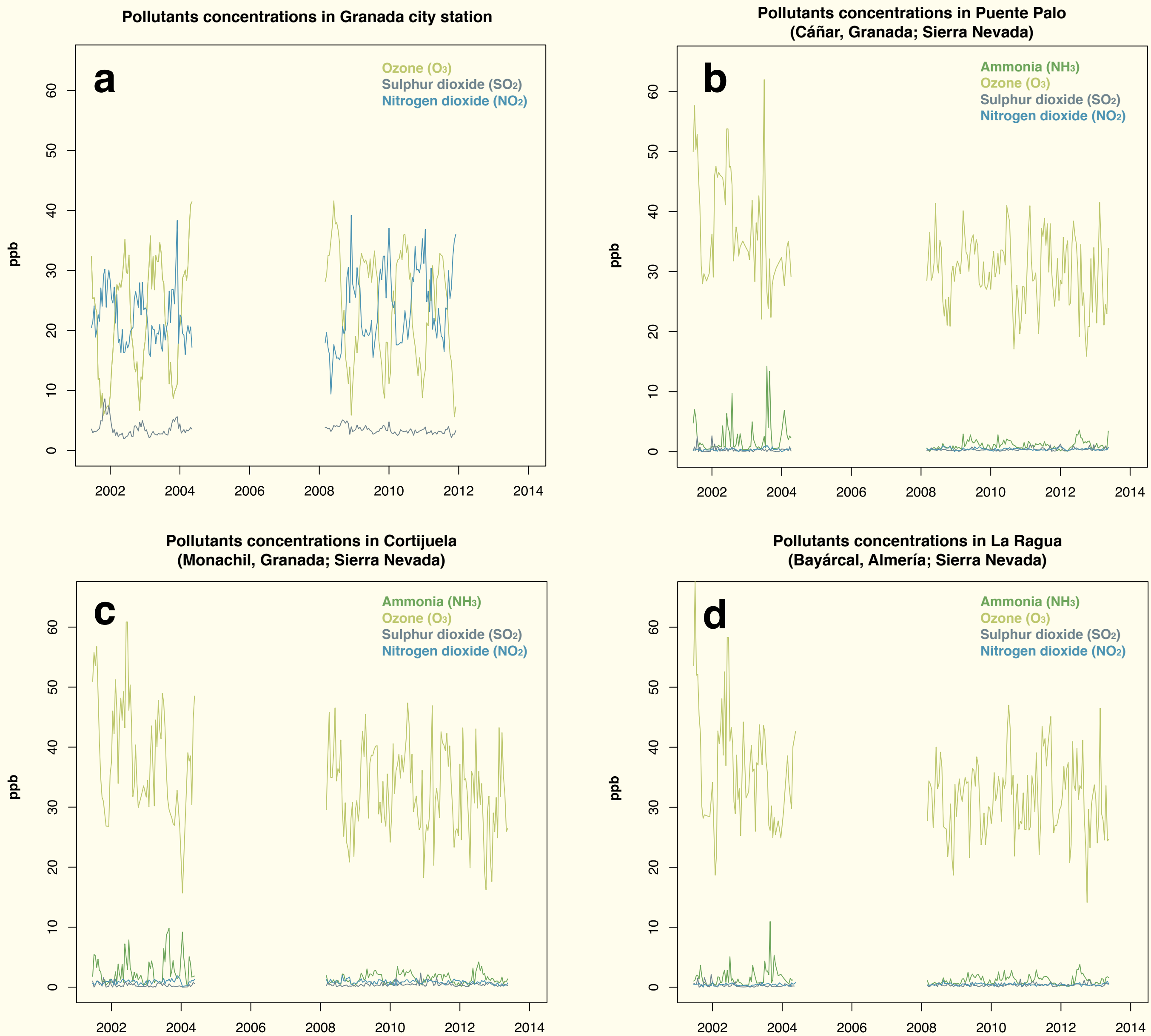
Ammonia, as well as ozone concentration, decreased in Sierra Nevada. Nevertheless, ozone remained relatively stable in Granada.

Finally, the SO_2 concentration rose slightly at the three points in Sierra Nevada, but kept the same range of values in Granada.

The available data are not sufficient to reliably predict future trends in the pollutants concentrations, especially without knowing the emission rate of the sources of each contaminant.

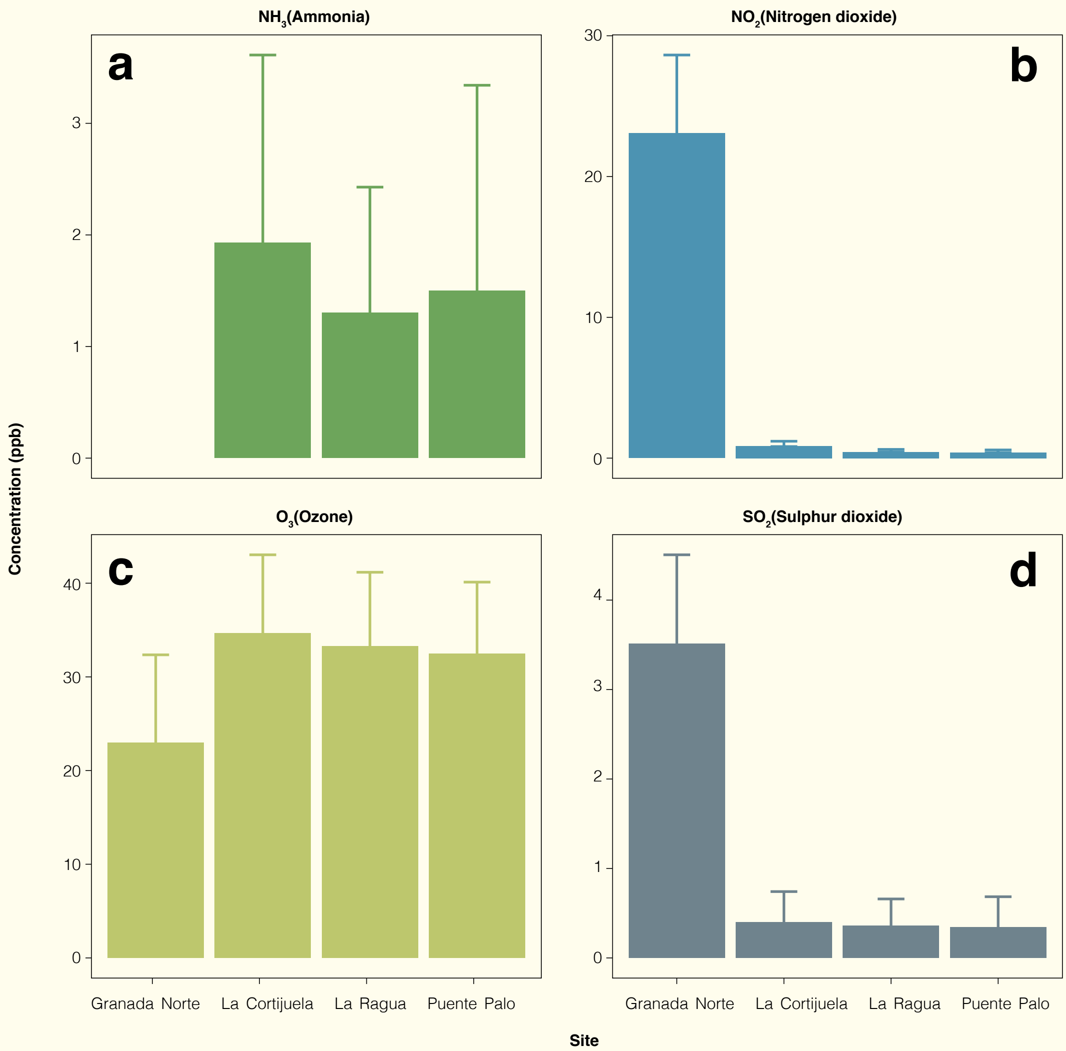
Nevertheless, the results of the projections indicate (Figure 4) that most have remained stationary, with a certain trend to decline in recent years (2012 and 2013).

Figure 1



Concentrations (in ppb) of each contaminant at 4 sites through time. a) Urban station of Granada; b) Puente Palo (Cáñar, Granada), pine and oak forests; c) La Cortijuela Botanic Garden, pine forest; d) La Ragua, pine forests and spiny broom thickets.

Figure 2



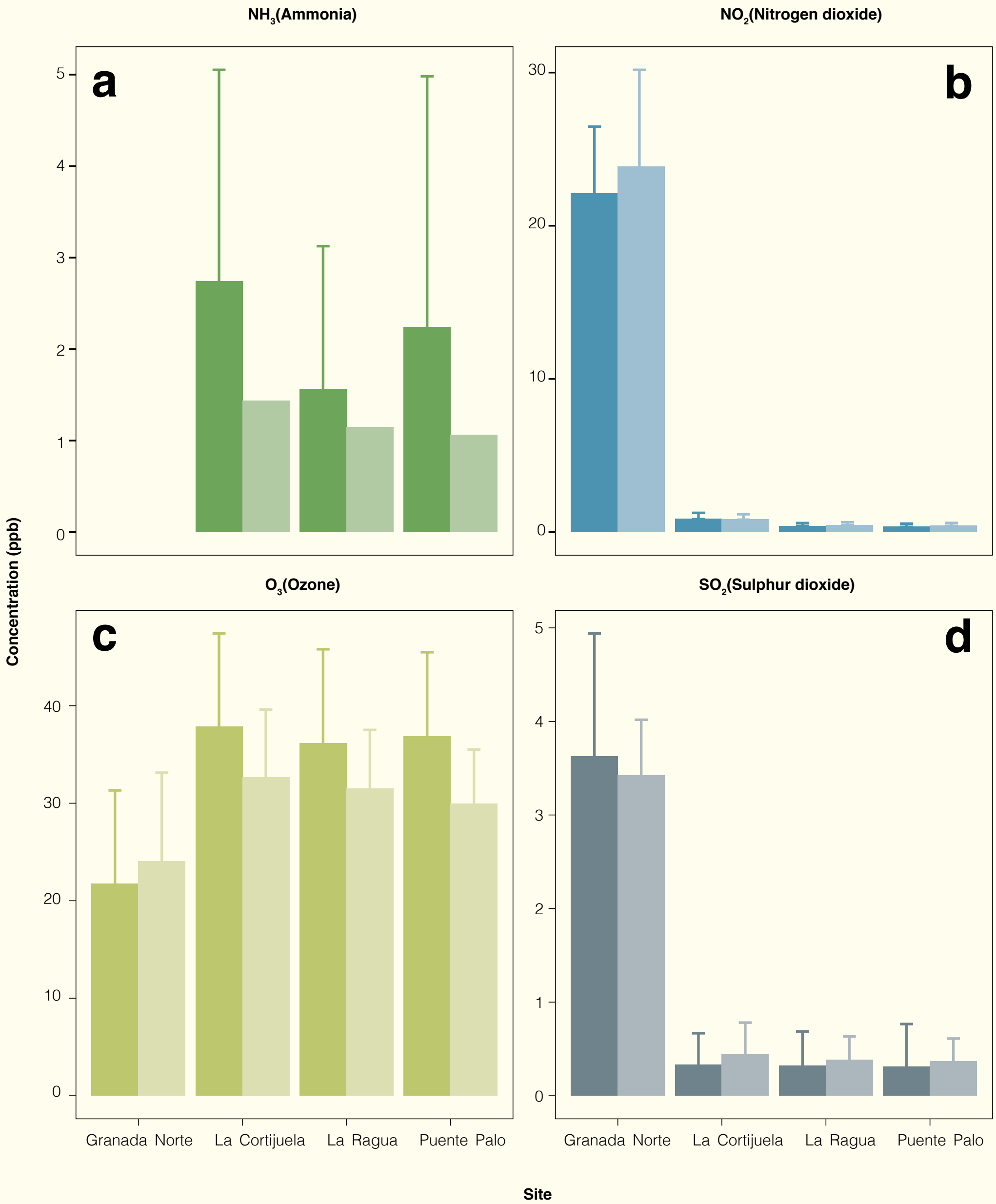
Distribution of concentrations (in ppb) of each contaminant during the period 2001-2013. a) Ammonia gas. No data are available for the city of Granada; b) Sulphur dioxide; c) ozone; and d) nitrogen dioxide.

› Discussion and conclusions

The comparative analysis confirmed that there is a great difference in contamination levels between Sierra Nevada Protected Area and the urban agglomeration of Granada, mainly in SO_2 and NO_2 concentrations.

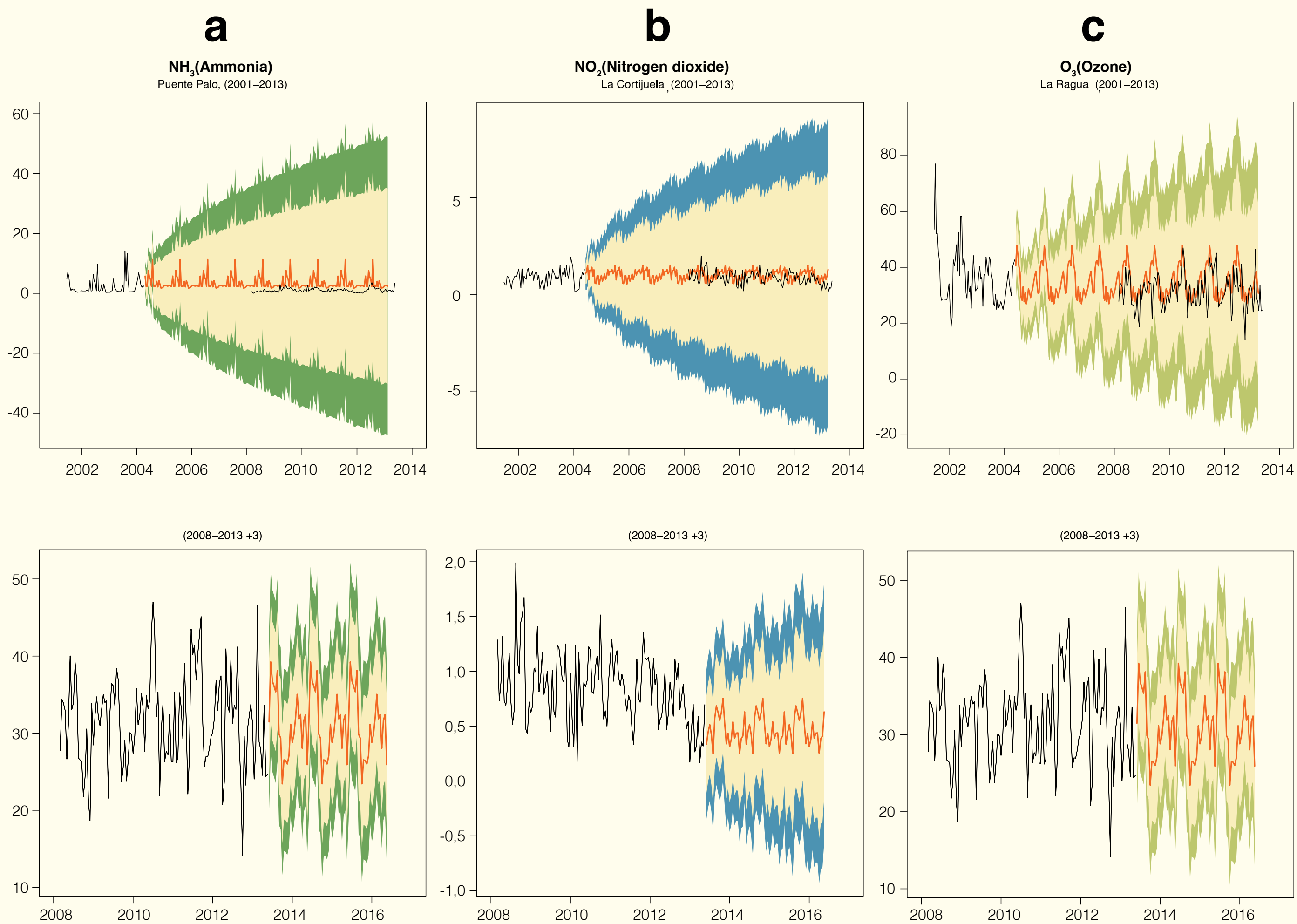
A decline was detected in the NH_3 and O_3 concentrations as well as a rise in the SO_2 and NO_2 concentrations in Sierra Nevada. There are not yet enough data to make a reliable forecast, although most pollutants seem to follow a stationary trend with a slight tendency to diminish at present.

Figure 3



Comparison of the distribution of concentrations (in ppb) of each contaminant for the 2 time series (2001-2004 and 2008-2013).

Figure 4



Three examples of superposition between the real values and the forecast for the next following years according to the current time course of the concentrations of ammonia (a), nitrogen dioxide (b), and ozone (c).

10.3. Monitoring the atmospheric deposition of aerosols in Sierra Nevada

Morales-Baquero, R.
University of Granada

Abstract

The deposition of atmospheric aerosols (dust) is a climatic variable that has not been taken into account until very recently. Therefore, the role that atmospheric depositions play in the biogeochemistry of Mediterranean ecosystems has not been sufficiently studied, although the data that are being reported indicate that the atmospheric particulated material, and especially Sahara Desert dust, represents one of the main inputs of nutrients and trace elements, among other components, to Mediterranean ecosystems. Concretelly, this study monitors the aerosols deposition in Sierra Nevada within a western Mediterranean context in relation to global climate change.

Aims and methodology

The quantification and variability of rainfall has been studied for some time with reliable time series that span decades and a relatively fine spatial resolution. However the genesis, mobilization, and deposition of suspended particles in the atmosphere are barely known. Arid areas are the main sources of aerosols and the Sahara Desert, the greatest of the entire planet, is responsible for the exportation of vast amounts of dust that are transported by the atmosphere towards the Atlantic Ocean and Europe.

The Mediterranean area receives, by particulate deposition, significant quantities of Ca, Fe, P, organic matter, and other elements without gaseous phases. The biogeochemical cycles of these elements have traditionally been considered closed within the ecosystems. Therefore, there is growing interest in quantifying these atmospheric fluxes and their impact on Mediterranean ecosystems. The aim of the present study is to establish a continuous data series on atmospheric aerosol deposition in Sierra Nevada and to study it in relation to climate change in order to predict its impact on those mountain systems.

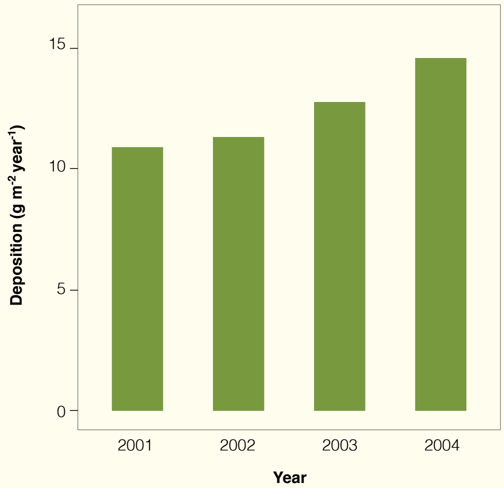
Since 2001 weekly samples of aerosol deposition have been collected in Sierra Nevada in two biennial series that lasted until 2005, with the exception of 2003. The samples were taken by passive automatic collectors that differentiate the dry deposition of aerosols from wet deposition (particles carried by the rain).

Currently, the weekly collection of particulate matter continues using a new automatic instrument installed in the weather station of Cañar, of the Regional Organization of National Parks, in coordination with the *CHARMEX* network, which is described below.

Results

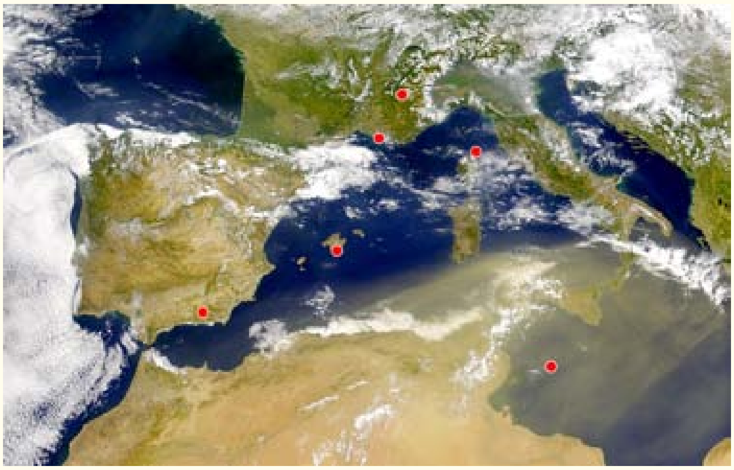
The data compiled show that more than 70% of the particulate matter is deposited in dry form, the rest carried by the rain. This reflects the singularity of the southern Mediterranean area in relation to more northern parts of the Northern Hemisphere, where the wet precipitation of aerosols is predominant. The evolution within the study period shows a progressive increase in the quantity of deposited material, ranging from 10.9 g m^{-2} $year^{-1}$ in 2001 to 14.6 g m^{-2} $year^{-1}$ in 2005 (Figure 1). Furthermore, the determinant influence of the deposition of organic carbon, phosphorus, nitrogen and calcium in the biogeochemistry of aquatic systems in Sierra Nevada has been demonstrated [11-14], as well as the determinant role of Saharan calcium inputs on Mediterranean forest [10].

Figure 1



Annual deposition of atmospheric particulate matter over Sierra Nevada

Figure 2



Deployment in the Western Mediterranean of the network of CARAGA collectors within the project *CHARMEX*.

Discussion and conclusions

The observed trend is consistent with the increase of Saharan dust emissions towards the Mediterranean region according to changes detected in global climate patterns. However, the data available are too scarce. Longer time series are needed to relate the dynamics of aerosols and their variability with other climatic variables.

Given the scarcity of data on aerosols their study has stirred interest in the scientific community and thus, French researchers coordinated by Professor François Dulac (Centre D'études Civils, Saclay) has promoted an initiative called: *CHARMEX* (The Chemistry-Aerosol Mediterranean Experiment). This project involves an ambitious long-term work plan that has the following objectives:

1. To establish the current state of the Mediterranean atmosphere.

2. To quantify the impact of reactive aerosols and gases.

3. To predict the future trends of these balances and impacts.

The specific aims cover a broad spectrum, including knowledge of radiative forcing, transport mechanisms, atmospheric chemistry, deposition, effects on ecosystems, and anthropogenic influence. Reaching these objectives implies the collaboration of a several groups of international researchers from different branches of science. This network currently consists of 7 nodes, 2 of which are in Spain: one in Majorca and the other in Sierra Nevada. In each node, an instrument that collects aerosols autonomously, called CARAGA, and developed specifically for this network, has been installed (Figure 2).

The network began to be deployed in 2010. In May of 2012, the autonomous collector was installed in the weather station of Cañar. During the first year, the functioning of this apparatus, which is a prototype, required various adjustments and sampling was irregular. From May 2013, weekly data were taken regularly and continue to be taken in a coordinated way with the rest of the stations of the *CHARMEX* network. With the collected data, critical information is expected to be compiled in order to validate the cycles and models of atmospheric depositions at the synoptic scale, as well as to know the past, present, and future role of these depositions on the functioning of Mediterranean ecosystems.

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› More references at http://refbase.iecolab.es/ref_dossier_resultados.html

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