Remote Sensing in Sierra Nevada: From Abiotic Processes to Biodiversity and Ecosystem Functions and Services

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Abstract

During the last decades, remote sensing has changed the way humans observe and understand the Earth system. The repeated and increasingly detailed observations made from satellite platforms and other remote sensing procedures have revolutionized research, particularly in the atmospheric and oceanographic sciences but also in the biophysical sciences. This chapter presents a systematic literature review of the different ways in which remote sensing has been applied in Sierra Nevada, Spain. Studies ranged from basic research to how remote sensing is actually contributing to management in this mountain biosphere reserve. The chapter is structured using the ecosystem services cascade as a framework, i.e., from studies on abiotic (i.e., geophysical, atmospheric, cryospheric, and hydrological) processes to research on biodiversity and ecosystem functions and services. The number of remote sensing studies in Sierra Nevada is quickly growing but still relatively scarce (only 65 records). Most of this research was either applied or use-oriented research and found to be potentially useful to assess biodiversity conservation status and ecosystem services, indeed it frequently contained recommendations for the management of the protected area. Hence, there is an expected increase in the interdisciplinary and transdisciplinary application of remote sensing to research in Sierra Nevada.

Keywords

Earth observation • Satellite • Drone • Unmanned aerial vehicle • Manned aerial vehicle • Airborne sensors • Radiometer • Multispectral • Spain

1 Introduction

1.1 Remote Sensing Definition and Types

Remote sensing is described as the process of detecting, obtaining, and monitoring the physical characteristics of objects or areas by measuring their reflected and emitted radiation from distance. In general, remote-sensing data about the Earth system are typically obtained through sensors onboard ex situ platforms, such as satellites, manned aerial vehicle, and unmanned aerial vehicles or ships. Nevertheless, Earth remote sensing sensors also enable capturing in situ measurements, e.g., by using spectroradiometers and cameras portable by hand or mounted on poles or towers, that are directly taken closer from the target object or area.

The longest history of use of remote sensing data over vast distances is dominated by spaceborne and airborne systems, targeting both passive (i.e., using the reflected sunlight) and active sensors (i.e., using an artificial light source) (Chuvieco and Huete 2009). Traditionally, the most used platforms in environmental sciences have been satellite

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passive sensors, such as Landsat (15–60 m/pixel), MODIS (250–1000 m/pixel), or the new Sentinel-2 (up to 10 m/pixel), but active sensors onboard satellites and aircrafts, such as LiDAR (Light Detection and Ranging) and microwave RADAR have significantly increased during the last decade. This technology, which offers excellent opportunities for monitoring all components of the Earth's surface, is attracting the interest of governments. Such is the case with the Copernicus program and its Sentinel-satellites constellation, the infrastructure of the European Space Agency, which is increasing our ability to analyze the Earth's surface through high spatial and temporal resolution imagery. In addition, since many objects and processes cannot be detected by very distant sensors, the use of lightweight unmanned aerial vehicles (UAVs) or drones, is opening a particularly cost-efficient way of collecting data at finer scales, but over smaller extents and restricted to strict flying regulations (Chen et al. 2021).

1.2 Applications of Remote Sensing in Environmental Sciences

Originally driven by military uses, remote sensing gradually evolved as a relevant technology in many scientific fields and for a variety of civil applications. Examples range from basic cartography for territorial planning, civil engineering, and emergency response, to meteorology, oceanography, agriculture, forestry, and natural resources assessment, among many others (Chuvieco and Huete 2009). Remote sensing data records allow continuous, updated, and cost-effective measures of the state and dynamics of many abiotic, biotic, and socioeconomic processes, hardly monitorable by other means at a global scale. For instance, satellite remote sensing data is considered the largest archive of biological information on Earth (Geller et al. 2017). Time series of surface reflectance in each band of the electromagnetic spectrum directly informs on the radiation and energy balance of each pixel around the Earth and indirectly on multiple aspects of the state and dynamics of life, such as photosynthesis (Hikosaka and Tsujimoto 2021), evapotranspiration (Chen and Liu 2020), wetness (Chandrasekar et al. 2010), land-use and land-cover (Rogan and Chen 2004), etc.

The use of remote sensing technology over local, regional, or global scales provides valuable information on the three dimensions of biodiversity (i.e., composition, structure, and function; Noss 1990) (Turner et al. 2003; Cabello et al. 2012, 2013; Nagendra et al. 2013; Pettorelli et al. 2016; Reddy 2021). Indeed, satellite remote sensing has been highlighted as a key tool to develop Essential Biodiversity Variables to inform on biodiversity status (Skidmore et al. 2021). Remote sensing can also provide inherent information to assess the macroecological drivers and trends of biodiversity patterns (Perry et al. 2009; Alcaraz-Segura et al. 2017; Arenas-Castro et al. 2018; Arenas-Castro et al. 2019; Regos et al. in press). The information provided by satellite data records on surface reflectance along the electromagnetic spectrum has not only been used to inform on biodiversity loss, a dramatically exceeded planetary boundary, whose control widely depends on the conservation of mountain environments, but also to assess the other environmental boundaries that define the safe operating space for humanity (Steffen et al. 2015). This is particularly the case for stratospheric ozone depletion, climate change, land-use change, atmospheric aerosols loading, biogeochemical flows, and freshwater use (Hughes et al. 2013).

Earth observation from remote sensors has also become essential to assess many aspects that directly affect human well-being such as those related to ecosystem functions and services (Alcaraz-Segura et al. 2013). Studies in this sense have been useful both for reporting on the ecosystem capacity to provide benefits to society (supply side), as well as the contributions of nature that are demanded by humans (demand side). Following the ecosystem services cascade as a framework (Potschin-Young et al. 2018; Czúcz et al. 2020), Earth observations have been widely applied in the basic study and characterization of geophysical and biophysical attributes, as well as of ecosystem processes and functions underlying ecosystem services provision (Alcaraz-Segura et al. 2013). From the demand side or social dimension of the ecosystem services cascade, remote sensors have also contributed to quantify the social goods, benefits, and values associated with ecosystem services (Vaz et al. 2020). In fact, remote sensing, together with geodesign, nature-based solutions, and artificial intelligence have become central in current European initiatives (e.g., COPERNICUS Program, GoGreenRoutes, LifeWatch ERIC) to address societal challenges, such as the United Nations' Sustainable Development Goals, providing environmental, social, and economic information needed to build social-ecological resilience and helping in the monitoring of the status and trends of biodiversity and ecosystem services in pursuit of sustainable solutions inspired and supported by nature.

1.3 Usefulness of Remote Sensing for Managing Protected Areas

Remote sensing can be a very useful tool for protected area managers (Nagendra et al. 2013; Rose et al. 2015). Managers need indicators sensitive to both long-term directional changes and near real-time processes to ensure a good understanding of ecosystem health (Lovett et al. 2007; Cabello et al. 2012). The indicators derived from remote sensing datasets allow for the monitoring and assessment of multiple responses of ecosystems to environmental changes and management actions. By using such indicators, protected area managers can adopt an adaptive management approach to evaluate the effectiveness of management actions (Westgate et al. 2013; Cabello et al. 2018). The convenience of remote sensing data to implement such an approach is due to its ability to reveal the drivers of long-term change with a consistent information update rate, while highlighting recent impacts on protected area conditions from the local to the regional scale (Cabello et al. 2016). In addition to these advantages, remote sensing has a much lower cost than repeated field measurements and field campaigns (Kennedy et al. 2009). The constant innovation in platforms and sensors enhances their potential performance, improving data acquisition resolution, signal/noise ratio, and in general, their quality. Thus, improving inputs allows us to adapt protected area monitoring programs to new ecological and societal challenges, which is of great importance considering the intensified impacts of climate and environmental change (Duan et al. 2020; Wang et al. 2020).

This chapter presents a thorough review of the multiple ways in which remote sensing has been applied in Sierra Nevada, from basic to applied research targeting abiotic, biophysical, and social-ecological attributes and processes to aid researchers, managers, and citizens in the comprehension and management of mountain environments. Despite remote sensing becoming the most powerful tool for monitoring ecosystems and biodiversity worldwide, many efforts (experimental, educational, and outreach) are still needed to actually incorporate it into environmental decision-making and management processes (Cabello et al. 2018). We consider that reviewing and ordering the advances done for Sierra Nevada according to the conceptual and regulatory frameworks followed by the protected area management teams will help to achieve this goal.

2 Materials and Methods

We performed a literature search of peer-reviewed publications using the whole collection of "ISI Web of Science" (ISI WOS; http://webofknowledge.com/) and Scopus (www.scopus.com) search engines during March, 2021. Our search structure, was adapted from Vaz et al. (2018), and focused on remote sensing applications in Sierra Nevada, Spain, considering the following search string:

> Title, abstract or keywords = ("Sierra Nevada") NOT ("California" OR "USA" OR "United States" OR "America" OR "colombia" OR "columbia" OR "Sierra Nevada de Santa Marta") AND ("remote sens*" OR "remote-sens*" OR "earth observation" OR "imagery" OR "UAV" OR "drone" OR "unmanned aerial" OR "aircraft*" OR "airborne" OR "air-borne" OR "spaceborne" OR "space-borne" OR "AVHRR" OR "radiomet*" OR "high-resolution" OR "high resolution" OR "very-high resolution" OR "high spatial resolution" OR "very-high spatial resolution" OR "hyper-spectral" OR "hyperspectral" OR "multispectral" OR "multi-spectral" OR "image fusion" OR "NDVI" OR "satellite*" OR "sensor*" OR "radar" OR "MODIS" OR "LiDAR" OR "sentinel*" OR "landsat*" OR "worldview*").

Our search retrieved 240 unduplicated records, which were then subjected to inclusion/exclusion criteria to eliminate irrelevant information (e.g., referred to Sierra Nevada in Colombia or in the USA or to a company named Sierra Nevada). Criteria were applied by checking the full content of each record individually, resulting in a final dataset of 65 relevant records. Each record was then fully reviewed to identify its potential use or actual ability to inform on: (1) Earth system components and types of targeted ecosystems; (2) explicit and implicit biodiversity dimensions (classified according to Noss 1990) and ecosystem services types (classified according to CICES version 5.1; Haines-Young and Potschin-Young 2018); (3) remote sensing platforms and products; and (4) types of research on and the management contributions to Sierra Nevada. To do so, we established a series of questions and categorical answers related to the former four attributes (Table 1).

3 Results

3.1 Overview on the Remote Sensing Research in Sierra Nevada

Most studies relied on satellite remote sensing (47%; Fig. 1a) and the most common products included MODIS (39%), Landsat (17%), AVHRR (7%), and Sentinel (3%). In situ remote sensing was the second most-used approach, being used alone or in combination with other approaches (16%). LIDAR was used in 11% of records. Unmanned (UAV) and manned aerial vehicles (MAV) accounted for a small proportion of records (3% and 2%, respectively), relying on orthophotography products used alone (3%) or in combination with LIDAR (7%; Fig. 1b).

Most records focused on terrestrial ecosystems only (40%) or both terrestrial and aquatic ecosystems (3%). Aquatic ecosystems alone were less addressed by remote-sensing means (3%). Most records did not explicitly focus their study neither on terrestrial nor on aquatic ecosystems (54%; Fig. 2a). We could notice a dominance of publications studying the biosphere and cryosphere (30% in each case), followed by the atmosphere (23%; Fig. 2b). The lithosphere and hydrosphere were less studied through remote sensing means (13% and 3%, respectively). A small number of records simultaneously studied interactions among several components of the Earth system. Regarding

Table 1 Categories used to assign each record retrieved by our search on remote sensing applications in Sierra Nevada

Questions	Categories
1. Remote sensing platforms and products	
Which type of remote sensing platform is being used in the record?	In situ
	Satellite
	Unmanned aerial platforms
	Manned aerial platforms
Which remote sensing product is being used/derived in the record?	LiDAR
	MODIS
	Landsat
	Others (specified in the record)
2. Type, components, and critical environmental boundaries of the targeted ecosystems	
Which type of ecosystems are being targeted in the record?	Terrestrial
	Aquatic
Which dimension of the Earth system is being targeted in the record?	Biosphere
	Atmosphere
	Cryosphere
	Hydrosphere
	Lithosphere
Which type of planetary boundary[1] does the record support? [1]Critical environmental boundaries to maintaining the Earth system within the functional space that ensures human well-being (Steffen et al. 2015)	Climate change
	Biodiversity loss
	Nitrogen cycle
	Phosphorus
	Water bodies acidification
	Land use
	Freshwater
	Ozone depletion
	Atmospheric aerosols
	Chemical pollution
3. Ecosystem dimensions and biodiversity conservation	
Is biodiversity conservation explicitly addressed in the record?	Yes
	No
Is the record potentially useful to inform on biodiversity conservation?	Yes
	No
Which ecosystem dimensions does the record focus on or is useful to assess?	Abiotic structure
	Biophysical structure
	Ecosystem function
	Ecosystem services
Are ecosystem services explicitly mentioned in the record?	Yes
	No
Is the record potentially useful to assess ecosystem services?	Yes
	No
Which ecosystem services (abiotic or biotic) does the record focus on or is useful to assess?	Specified based CICES v5.1 (Haines-Young and Potschin-Young 2018)
Which biodiversity dimension (i.e., composition, structure, or function) does the record focus on or is useful to assess (according to Noss 1990)?	Function
	Structure
	Composition

(continued)

Table 1 (continued)

Questions	Categories
4. Type of research and management contributions	
Which type of research is shown in the record?	Applied
	Basic
	Use-oriented
Does the record present any explicit implications for management?	Yes
	No

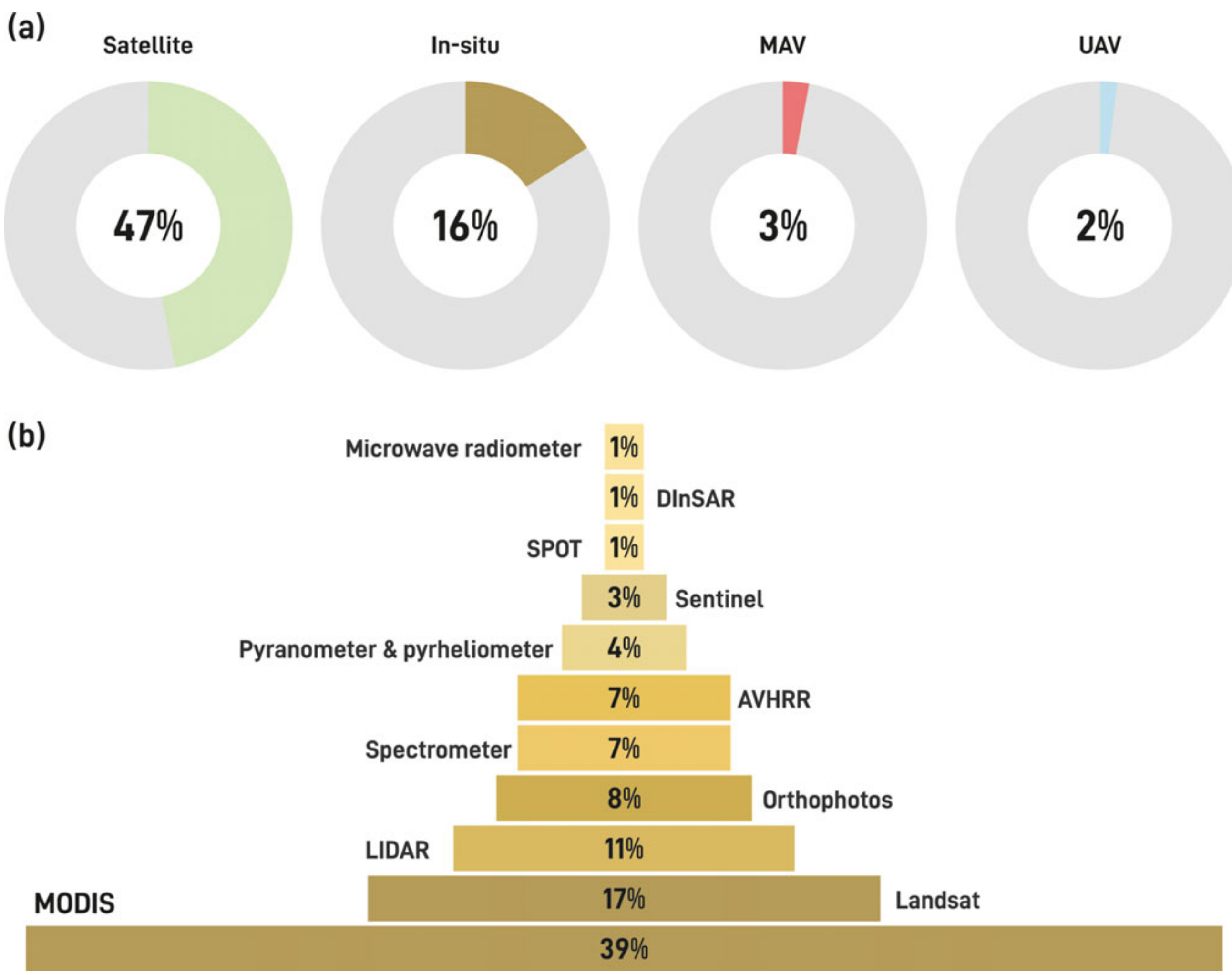

Fig. 1 Proportion (%) of records according to different remote sensing platforms (**a**): satellite, in situ, manned (MAV), or unmanned aerial vehicle (UAV) and relying on different remote sensing products (**b**)

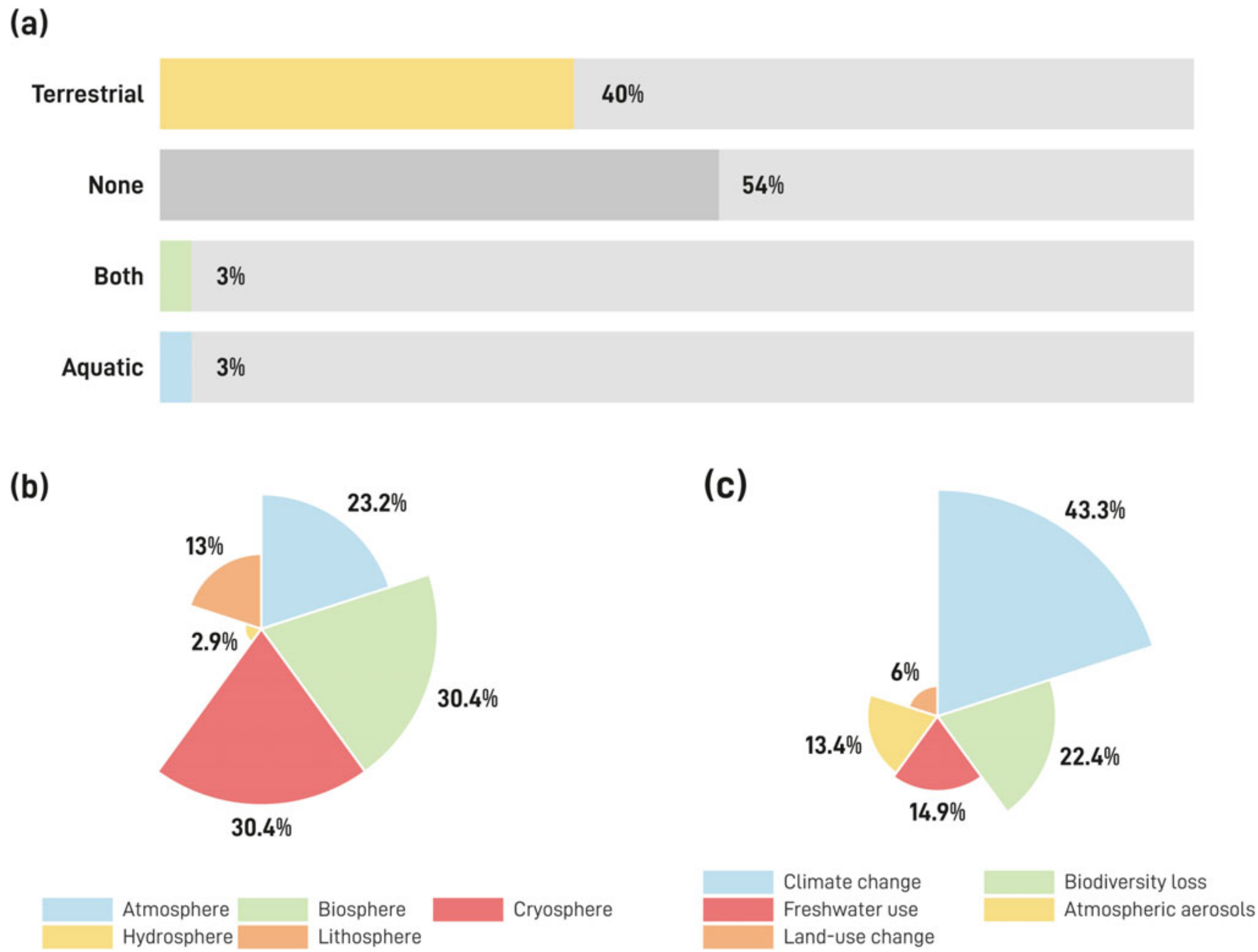

Fig. 2 Proportion (%) of records per ecosystem type (**a**), and targeting different Earth subsystems (**b**) and planetary boundaries (Steffen et al. 2015) (**c**)

the potential of the retrieved records on the use of remote sensing in Sierra Nevada to assess the nine planetary boundaries, almost half of the records could be used to assess climate change (43%), followed by issues related to biodiversity loss (22%), freshwater use (15%), atmospheric aerosols (13%), and land-use change (6%; Fig. 2c). None of the records explicitly mentioned the planetary boundaries framework.

The vast majority of records did not explicitly address biodiversity (69%) nor ecosystem services (97% of all records) (not shown in figures). However, the findings presented in some of the retrieved records could potentially be useful for the management and conservation of biodiversity (20%), ecosystem functions (22%), or services (1%; Fig. 3 a). Focusing on those records that assessed or were found useful to infer on any dimension of biodiversity (alone or in combination with other/s dimension/s), 66% informed on biodiversity function, whereas 16% and 15% showed useful information for biodiversity structure, and composition, respectively (Fig. 3b). The great majority of records informed on the functional dimension of biodiversity alone (55%), or in combination with biodiversity composition or structure (12% and 11%, respectively). Records exclusively addressing biodiversity structure were very low (3%), with no studies exclusively addressing biodiversity composition (0%). A holistic view on biodiversity (i.e., comprehensive use of remote sensing for the integrated assessment of biodiversity composition, structure, and function) was found in only 8% of records. Eleven percent (11%) of records were not clearly found to be useful to address any biodiversity dimension. Records focused on ecosystem functioning mostly targeted the assessment of primary production and water and energy balance. The biophysical structure, and particularly, the assessment of land cover, was identified in 5% of records.

Records assessing ecosystem services or found useful to infer about them, mostly focused on abiotic ecosystem services (71%), specifically on provisioning (38%), regulating

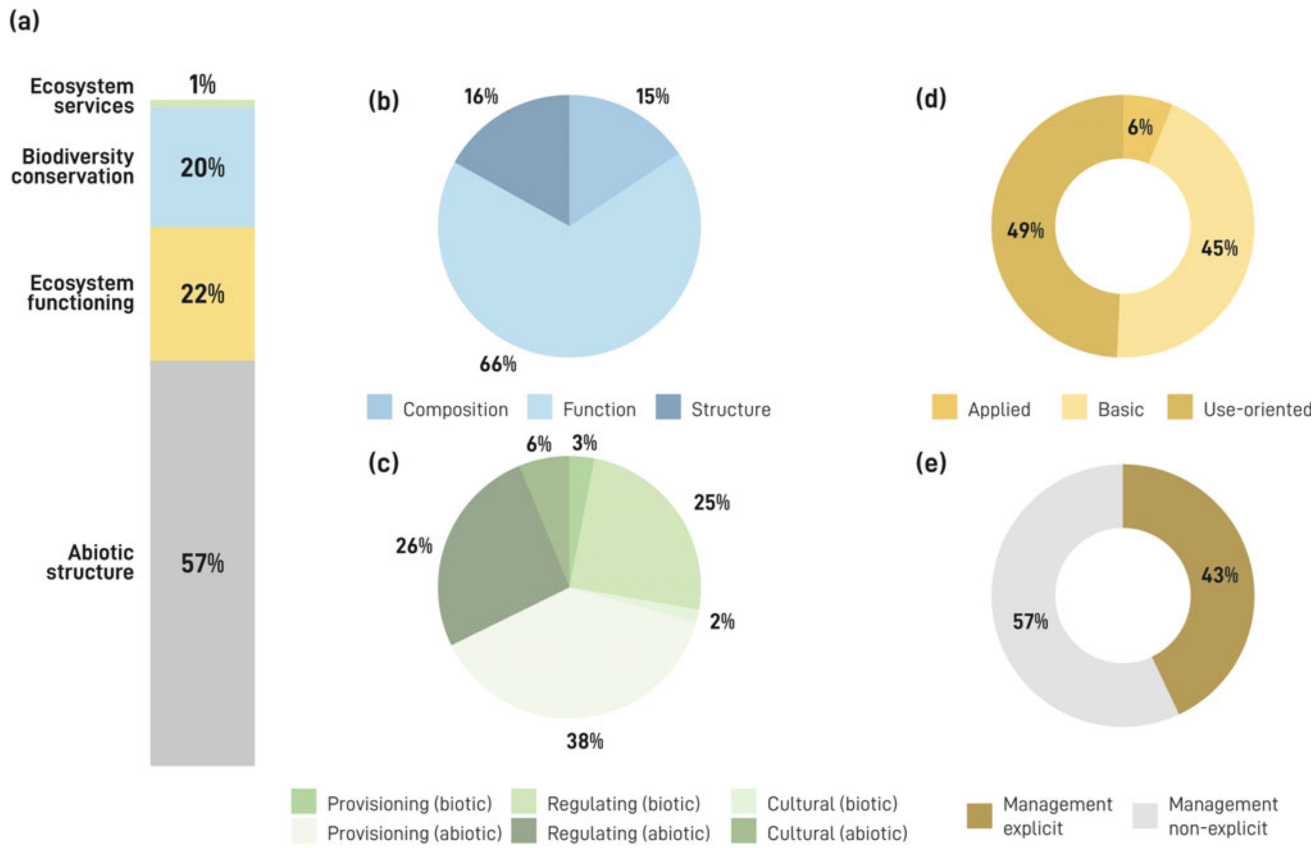

Fig. 3 Proportion (%) of records potentially (but not explicitly) useful to address abiotic structure, ecosystem functioning, biodiversity conservation and ecosystem service (**a**), and the respective biodiversity dimensions (**b**) and types of ecosystem services (**c**). The figure also shows the proportion of records classified as use-oriented research, basic research, and applied research (**d**), as well as explicitly mentioning or not any management implications for the protected area (**e**)

(26%), and cultural services (6%; Fig. 3c). A high proportion of studies dealing with snow and water dynamics could be used to assess abiotic provisioning services related to "Surface water used for nutrition, materials, or energy" (31%), and abiotic cultural services related to "Physical and experiential interactions with natural environment." Many studies on atmospheric aerosols could be useful to assess abiotic regulating services related to "Regulation of physical, chemical, biological conditions" (23%). The production of solar energy was another abiotic provisioning service with a noticeable number of records (5%). A great proportion of papers also focused on biotic services (29%), being biotic regulating services the most abundant (25%), followed by provisioning (3%) and cultural services (2%; Fig. 3c). Mostly, biotic regulating services related to the "Regulation of physical, chemical, biological conditions," in particular with the "Maintenance of nursery populations and habitats" (20%).

Finally, most of the insights derived from remote sensing platforms and products were classified as use-oriented research (49%), or as basic research (45%). Only 6% of records were found to include applied research (Fig. 3d). Inevitably, more than half of the remote-sensing studies developed in Sierra Nevada Natural and National Park do not present or discuss any implications for managing the protected area (57%; Fig. 3e).

4 Discussion

4.1 Abiotic Processes

As expected, research on snow cover dynamics and trends was dominant in Sierra Nevada since it is a high mountain under a Mediterranean climate with a ski resort, and surrounded by irrigated agricultural fields and urban areas that frequently face snow and water scarcity (Climate Variability and Trends). Snow cover, snow depth, and snow melt have been extensively modeled in Sierra Nevada considering factors such as radiation, temperature, wind, relief, and vegetation cover and validated using both Landsat (e.g., Herrero et al. 2011; Pimentel et al. 2013) and MODIS (e.g., Pimentel et al. 2018), and Sentinel-1 and Sentinel-2 (e.g., Pratola and Navarro-Sánchez 2018) products. Snow effects on surface energy balance through albedo (Pimentel et al. 2016), on water balance through snow-water equivalent (Collados-Lara et al. 2020), on photosynthesis (Pérez-Luque et al. 2015), and on evapotranspiration, downstream irrigation use (Vivas et al. 2016), river discharge, and aquifer recharge (Jódar et al. 2018) have also been studied and modeled making use of satellite imagery. Past trends and future scenarios of snow cover in Sierra Nevada have been studied using remote sensing data (e.g., Collados-Lara et al. 2019). In situ terrestrial photography has also been key to validate the remote sensing products and model outputs (Pimentel et al. 2017; Polo et al. 2019). In summary, during the last two decades, remote sensing has been essential in developing the high level of knowledge reached on snow and water dynamics in Sierra Nevada, resulting in several independent calibrated models of snow and water dynamics that aim to be used in actual management. Overall, these studies show a decreasing trend in the persistence and extent of the snow cover area, being the precipitation regime, rather than the temperature trend, the most relevant driver on the snow regime forcing (Pérez-Palazón et al. 2015). In addition, the ongoing LACEM-LIM Project is assessing the use of satellite remote sensing together with social science (Advancing Open Science in Sierra Nevada: Current Citizen Science Campaigns) for the assessment of water level dynamics in the high mountain lakes of Sierra Nevada.

Atmospheric dust transportation (Alados-Arboledas et al. 2007; Israelevich et al. 2012) and aerosol properties, dynamics, and optical depth (e.g., Román et al. 2018) have also been extensively assessed and modeled mainly by making use of in situ remote sensing technologies, such as LIDAR and microwave radiometers (e.g., de Arruda Moreira et al. 2018), but also based on satellite imagery (e.g., Israelevich et al. 2012) and airborne sensors (Román et al. 2018). As a result, there is much-accumulated knowledge on the regional dynamics of dust transportation, aerosol properties, and their effects on air quality (de Arruda Moreira et al. 2018), ultraviolet radiation (Estellés et al. 2006), and spatio-temporal impacts on satellite vegetation indices (Reyes-Díez et al. 2015). Currently, most of this knowledge has not yet been transferred for the actual management of the Sierra Nevada protected area. However, dust intrusions and depositions have enormous effects on the composition, structure, and function of biodiversity in oligotrophic mountain lakes and rivers of Sierra Nevada. Hence, there is a huge potential for interdisciplinary and transdisciplinary research to quantify, characterize, and model the fertilization effect of aerosols, not only on aquatic, but also on the terrestrial ecosystems of Sierra Nevada. Remote sensing is expected to catalyze this collaboration under the LifeWatch SmartEcoMountains project.

Solar irradiance has been another abiotic factor widely studied in Sierra Nevada using remote sensing. A network of in situ remote sensors has been used to model solar irradiation over the complex terrain of Sierra Nevada (Bosch et al. 2008). Models of solar irradiation and subsequent effects on soil and atmospheric temperature and relative humidity have also been developed using MODIS satellite imagery (López et al. 2014). The inputs and outputs of these models, such as solar irradiation, precipitable water vapor, soil and atmospheric temperature, and relative humidity, have valuable implications for the management of Sierra Nevada protected area since they relate to direct abiotic services, such as solar energy production, and to biotic processes, such as photosynthesis and evapotranspiration.

Geomorphological studies related to landslides and paleoglacier morphology using remote sensing have also been frequent in Sierra Nevada. Landslides and floods have a long history in Sierra Nevada, showing high potential for ecological and socioeconomic (Jiménez et al. 2018). Both terrestrial and airborne LIDAR have been intensively used, together with orthophotography, to inventory, assess, and monitor multiple landslides in Sierra Nevada (e.g., Palenzuela et al. 2016). The use of satellite radar (i.e., D-InSAR) information has recently allowed the production of a landslide-risk map of Sierra Nevada (Jiménez-Perálvarez 2017), which has a direct application in the management of the protected area. In the case of glacier morphology, terrestrial LIDAR and airborne orthoimagery also allowed to characterize the glacial and postglacial evolution in Sierra Nevada (Gómez-Gutiérrez et al. 2014; Gómez-Gutiérrez et al. 2015; Gómez-Gutiérrez et al. 2016). Recently, based on the photointerpretation of very high-resolution satelite imagery (ESRI World and Google Earth imagery), a management-ready glacial and periglacial geomorphological map of Sierra Nevada has been produced (Palma et al. 2017).

4.2 Biodiversity Composition and Structure

The use of remote sensing to assess biodiversity and ecosystem functions and services have been restricted to satellite imagery so far. The scarcity of studies directly assessing biodiversity composition might be related to the relatively recent and expensive availability of very high-resolution imagery needed for the direct identification of species (but see Guirado et al. 2017; Blanco-Sacristan et al. under review). The severe weather conditions and abrupt relief of this high mountain have also restricted the use of UAV and MAV sensors. Nonetheless, the DETECTOR project is currently being developed (Alcaraz-Segura et al. in prep.) to fuse drone, airborne, and satellite very high-resolution imagery with deep learning neural networks to produce a wall-to-wall map of all individuals of several high-mountain shrub species in Sierra Nevada. The incorporation of satellite information into species distribution models is also opening an opportunity for the direct assessment of habitat suitability for many plants and animals at the species level (e.g., Arenas-Castro et al. 2018, 2019; Regos et al. 2019). In Sierra Nevada, we are only aware of the ongoing study of changes in the habitat suitability of *Moehringia fontqueri* Pau with the use of Landsat land surface temperature (Julio Peñas et al. in prep., personal communication).

Despite the low number of studies, remote sensing has been successfully used for the conservation status assessment of species and habitats. MODIS satellite products of vegetation indices and snow have been used to assess and model the effects of the temporal dynamics in primary productivity and snow on the demography, parasitism, forage availability, and ethology of *Capra pyrenaica* Schinz populations (Carvalho et al. 2015; Viana et al. 2018). The interannual variability and trends in MODIS vegetation indices have also been used to assess the vulnerability and conservation status of hotspots of endemic butterflies (Aragón et al. 2019) and of all southernmost remnant populations of *Quercus pyrenaica* Willd. of the Iberian Peninsula (Dionisio et al. 2012). The Global Change Observatory of Sierra Nevada has also developed an ontological system based on MODIS images to help in the assessment of the conservation status of Natura 2000 habitats (Pérez-Luque et al. 2015), intended to be used by managers for the Art. 17 Habitats Directive 6-year reporting (Schröder et al. 2013).

4.3 Ecosystem Processes and Functions

Ecosystem functioning has been by far the most frequent biodiversity dimension studied by remote sensing means in Sierra Nevada. All studies are restricted to the use of satellite estimators of primary production and range from the characterization of its seasonal dynamics, to the detection of long-term trends (Alcaraz-Segura et al. 2008a, 2008b; Alcaraz-Segura et al. 2009), and their local (Pérez-Luque et al. 2015; Alcaraz-Segura et al. 2016) and regional drivers (Lourenço et al. 2018). Satellite-derived descriptors of primary production dynamics have also been used to characterize ecosystem functional heterogeneity, diversity, and rarity to set geographic conservation priorities (Cabello et al. 2008, 2013; Cazorla et al. 2020). Remote-sensing estimators of primary production have dominated studies on Sierra Nevada so far. This finding may not be a surprise considering that primary production is at the bottom of the food chain and many ecological processes, and offers the most integrative response to environmental drivers (Virginia and Wall 2013). Still, many other aspects of ecosystem functioning (e.g., albedo, land surface temperature, evapotranspiration, water content, etc.) with clear and relevant ecological implications can also be assessed by remote sensing means (Arenas-Castro et al. 2019; Marcos et al. 2019, 2021). From our review, we could find only one study addressing long-term dynamics of land surface temperature using MODIS (Palade and Serrano 2014) and another one calibrating vegetation parameters to estimate evapotranspiration using Landsat (Carpintero et al. 2018). Incorporating these multiple aspects of ecosystem functioning to REMOTE, the official monitoring system of the Spanish National Parks Network Organism (Cabello et al. 2016), and ease the use of a variety of remote sensing products by scientists and managers is one of the objectives of the ongoing projects LIFE Adaptamed and LifeWatch SmartEcoMountains. At present, there is still no study explicitly addressing either biodiversity or ecosystem functioning and services in the aquatic ecosystems of Sierra Nevada using remote sensing. This gap should soon be filled by LifeWatch SmartEcoMountains project in collaboration with the ongoing LACEM-LIM project (Advancing Open Science in Sierra Nevada: Current Citizen Science Campaigns), which makes use of satellite remote sensing for the assessment of water level and chlorophyll and other pigments in the high mountain lakes of Sierra Nevada with Sentinel-2 and WorldView-3 imagery.

4.4 Ecosystem Services

Most of the remote sensing studies in our dataset were found to be useful for the assessment of biotic or abiotic ecosystem services in Sierra Nevada. However, only the article by Vaz et al. (2020) had as main purpose the actual assessment of final ecosystem services through the use of remote sensing means, and it was the only one addressing cultural services in Sierra Nevada. Most of the articles addressing ecosystem functions acknowledge that their study relates to intermediate provisioning or regulating ecosystem services (Potschin-Young et al. 2017), but none of them directly addressed final services as specified in the CICES classification (Haines-Young and Potschin-Young 2018). However, given the connection of intermediate services with final services via supply or production functions (Paruelo and Vallejos 2013), it is expected that much of the knowledge gained on ecosystem functions in Sierra Nevada could be soon translated to actual final ecosystem services.

5 Concluding Remarks and Research Gaps

Despite the vast investment on Earth Observation programs such as Copernicus in the European Union, the number of actual studies that make any use of remote sensing data or methods in Sierra Nevada is still very scarce. One of the reasons could be the high level of specialization required to use or produce remote sensing data together with the scarcity of undergraduate and postgraduate studies on remote sensing in southern Spain, particularly in the University of Granada, the research center that has produced most of the research on Sierra Nevada (see chapter "Scientific Knowledge Generated in Sierra Nevada: Bibliographic Review (1970–2021)" of this book). In addition, remote sensing experts are very much attracted to the private sector and, due to their transdisciplinary profiles, do not easily fit in the traditional disciplinary structure of university and research center departments.

One of the positive messages of our review is that most of the research conducted in Sierra Nevada via remote sensing means is potentially useful to assess biodiversity and ecosystem services, and that most of it was either applied or use-oriented research, frequently already containing recommendations for the management of the protected area. Hence, an increase in the interdisciplinary and transdisciplinary application of remote sensing to research in Sierra Nevada is expected.

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