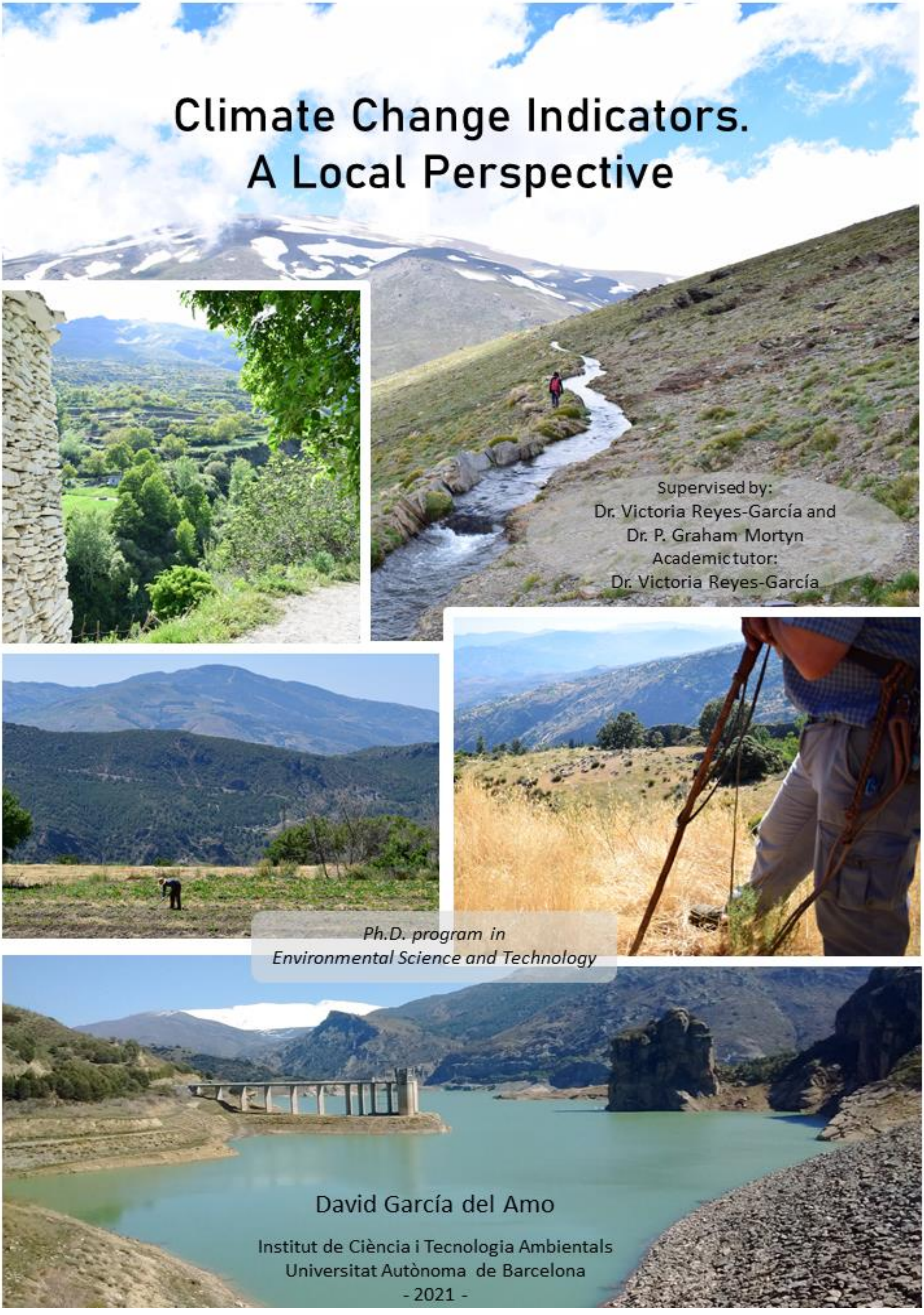
Universitat Autònoma de Barcelona

Climate Change Indicators. A Local Perspective

David García del Amo



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Supervised by:
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Dr. P. Graham Mortyn
Academic tutor:
Dr. Victoria Reyes-García

Ph.D. program in
Environmental Science and Technology

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Institut de Ciència i Tecnologia Ambientals, ICTA

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This thesis was developed at the Institute of Environmental Science and Technology (ICTA) of the Autonomous university of Barcelona from December 2016 to July 2021, being a member of the research group *Laboratory for the Analysis of Social-Ecological Systems in a Globalised World (*LASEG), led by Dr. Victoria Reyes-García and Dr. Esteva Corbera Elizalde. During the thesis period, a research stay was made at Granada University, under the supervision of J.M. Martín Civantos (2018), at the *Laboratory of Memoria Biocultural (MEMOLAB).*

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For this thesis, field work has been carried out during eight months in Sierra Nevada, Spain, working with members of local communities. To conduct the field work, this research has received the approval of the Ethics committee of the Autonomous University of Barcelona (CEEAH 3581 and CEEAH 4781).

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Cover photo: Composition of Sierra Nevada pictures. Author: David García del Amo

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A Eldur

Porque no siempre lo urgente es lo importante

A mis padres

A los habitantes de los pueblos de Sierra Nevada

Hay un único lugar donde ayer y hoy se encuentran,
y se reconocen y se abrazan,
y ese lugar es mañana.

Suenan muy futuras ciertas voces del pasado muy pasado.
Las antiguas voces, pongamos por caso,
que todavía nos dicen que somos hijos de la tierra,
y que la madre no se vende ni se alquila.
Mientras llueven pájaros muertos sobre las ciudades,
y se convierten los ríos en cloacas,
los mares en basureros
y las selvas en desiertos,
esas voces porfiadamente vivas nos anuncian otro mundo,
que no es este mundo envenenador del agua, el suelo, el aire y el alma.

También nos anuncian otro mundo posible
las voces antiguas que nos hablan de comunidad.
La comunidad, el modo comunitario de producción y de la vida,
es la más remota tradición de las comunidades,
la más comunitaria de todas:
pero también pertenecen a los tiempos que vienen
y presiente un nuevo Nuevo Mundo.

Adapted from “*Las tradiciones futuras*”

Eduardo Galeano –

El libro de los abrazos

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Considero que el primer requisito para poder terminar un proyecto largo y estar satisfecho con el resultado es tener unos buenos cimientos, y en el caso de la tesis doctoral, estos cimientos los representan los supervisores, por lo que en primer lugar me gustaría agradecer a Viki y Graham su ayuda y colaboración, tanto a nivel profesional como personal, a lo largo de este camino. A Viki, por su infinita capacidad de esfuerzo y superación, por su enorme entusiasmo por la investigación y su mágica capacidad de transmitirlo a quien la rodea. Me siento muy afortunado de estos casi cinco años trabajando a tu lado. Nunca llegué a imaginar que terminaría haciendo mi tesis doctoral con la famosa Reyes-García a quien yo leía y citaba en mi primer trabajo de master allá en 2010. Durante estos años he aprendido mucho contigo y espero poder seguir haciéndolo en el futuro. Muchas gracias por ayudarme a ver las oportunidades en medio de la adversidad y por confiar en mi más de lo que yo mismo hacía en algunas ocasiones. A Graham, por su calma y serenidad, y su capacidad de ver siempre el vaso medio lleno. Gracias por tu esfuerzo en la comprensión y adaptación a nuevos marcos conceptuales completamente distintos a tus habituales líneas de investigación. También por tu visión crítica y constructiva y tu ayuda inmediata siempre que la he necesitado. A ambos, me gustaría agradeceros todo el apoyo personal que me habéis dado. Hacer una tesis doctoral no es sólo cuestión de números y artículos publicados, sino que detrás hay personas con problemas más allá de los puramente académicos, los cuales son en muchos casos más determinantes que los resultados estadísticos. Por eso, considero que habéis sido unos excelentes supervisores de tesis, considerando estos factores con la misma importancia que los puramente profesionales.

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Summary

This thesis contributes to the growing research field of climate change and indigenous and local knowledge (ILK) by answering the call for the exploration of ground data sources that will help fill current gaps in our understanding of climate change impacts at the local level. Indeed, climate change, together with other natural and anthropogenic drivers of change, is generating very unequal impacts around the Earth. Although during the last decades researchers have improved their predictions of local impacts using computational models, our understanding of local impacts of climate change is still meagre. My work offers a comprehensive view of the main problems identified by researchers regarding ILK contribution to climate change impacts research and it does so by combining inputs from different sources of knowledge. Specifically, in this thesis, I have analyzed local climate change impacts perceived by rural communities of a mountain area (Sierra Nevada, Spain) and investigated the problems associated with prediction models at regional scales. I have also used inputs from local knowledge to analyze interactions and cascading effects between different climate change impacts and the capacity of rural communities to differentiate impacts derived from climate and other drivers of change.

Results from my Ph.D. work are organized into three chapters. My first empirical chapter addresses the relevance of ILK in research on climate change impacts. The chapter analyses scientific publications addressing climate change impacts and ILK. I contrast results from this literature review with the opinions of climate change researchers regarding the need to collect local level data to improve current knowledge on climate change impacts and the potential of ILK to contribute to that goal. I found that, while climate change researchers considered necessary to continue collecting local level data to understand impacts on climatic, physical, biological and human elements, they suggested that ILK could contribute mainly to the understanding of impacts on the biological and human systems. However, results of the literature review show that researchers have mostly focused on climate change impacts on elements of the climatic and physical systems. In other words, my research suggests that there is a mismatch between the contributions that climate change researchers expect from ILK and the actual focus of the research being conducted by researchers working with indigenous peoples and local communities.

The second empirical chapter uses a classification of local indicators of climate change impacts (LICCI) to organize observations of environmental impacts collected among inhabitants of rural communities of Sierra Nevada (Spain). In particular, I collected local perceptions of climate change impacts perceived by people with a historical relation with the environment and examined how such perceptions varied across geographical settings and sociodemographic factors. I conducted the fieldwork in 33 municipalities grouped into eight areas of the same region where I interviewed 238 people, including farmers, shepherds, ranchers, beekeepers, and other informants who conduct those activities for self-consumption. I analyzed respondents' perception regarding changes in 95 indicators of climate change impacts identified in the literature. 80% of respondents reported changes in more than one third of the indicators, with an average of 52 indicators perceived by each respondent. I also found differences in perception across the different geographical zones of the study region, and across informants' sociodemographic characteristics, including personal and familiar permanence to the region and level of interaction with nature.

In my final empirical chapter, I use information from the same survey to address the relation among climate change and other drivers of change. This chapter provides a deeper analysis of the local communities' views of environmental changes through network analysis. It shows interactions among climate change impacts perceived by local communities, revealing the most important impacts perceived in their social-ecological systems and the cascading effects of climate change impacts in the physical, biological and human systems. Results of the networks analysis of climate change impacts perceived show that impacts in elements of the climatic and physical systems are perceived by local communities as the most damaging for their livelihoods. But climate change impacts in some biological and human components were perceived as key elements of the network due to their repercussion in other elements through cascading impacts. Respondents perceived climate change as a main driver of change acting in the region, although they identified eight other direct and indirect drivers generating environmental changes in the region, often adding to climate change pressures. Respondents identified the human system and then the climatic system as the most affected by the combined effects of the different drivers of change.

This thesis contributes to bridging western science and ILK within the framework of climate change. Results suggest that ILK should be considered as an independent and valid source of knowledge with its own framework. ILK could complete deficient scientific data records at local level, particularly regarding impacts on the biological and human systems. Moreover, results of the thesis show geographical differences within the region regarding climate change impacts, supporting the idea to develop evaluation and adaptation plans at local levels to avoid future inequities due to unevenly distributed impacts.

Resumen

Esta tesis contribuye al creciente campo de investigación del cambio climático y el conocimiento indígena y local (ILK) respondiendo al llamado para la exploración de fuentes de datos terrestres que ayudarán a llenar los vacíos actuales en nuestra comprensión de los impactos del cambio climático a nivel local. De hecho, el cambio climático, junto con otros impulsores de cambio naturales y antropogénicos, está generando impactos muy desiguales alrededor de la Tierra. Aunque durante las últimas décadas los investigadores han mejorado sus predicciones de los impactos locales utilizando modelos informáticos, nuestra comprensión de los impactos locales del cambio climático es todavía escasa. Mi trabajo ofrece una visión integral de los principales problemas identificados por los investigadores con respecto a la contribución del ILK a la investigación de los impactos del cambio climático, y lo hace combinando insumos de diferentes fuentes de conocimiento. En concreto, en esta tesis he analizado los impactos locales del cambio climático percibidos por las comunidades rurales de una zona de montaña (Sierra Nevada, España) e investigado los problemas asociados a los modelos de predicción a escalas regionales. También he utilizado aportes del conocimiento local para analizar las interacciones y los efectos en cascada entre los diferentes impactos del cambio climático y la capacidad de las comunidades rurales para diferenciar los impactos derivados del clima y otros impulsores de cambio. Los resultados de mi trabajo de doctorado se organizan en tres capítulos.

Mi primer capítulo empírico aborda la relevancia de ILK en la investigación sobre los impactos del cambio climático. El capítulo analiza las publicaciones científicas que abordan los impactos del cambio climático y el ILK. EN él comparo los resultados de esta revisión de la literatura con las opiniones de los investigadores especializados en cambio climático con respecto a la necesidad de recopilar datos a nivel local para mejorar el conocimiento actual sobre los impactos del cambio climático y el potencial de ILK para contribuir a ese objetivo. Descubrí que, si bien los investigadores del cambio climático consideraban necesario continuar recopilando datos a nivel local para comprender los impactos en los elementos climáticos, físicos, biológicos y humanos, sugirieron que ILK podría contribuir principalmente a la comprensión de los impactos en los sistemas biológicos y humanos. Sin embargo, los resultados de la revisión de la literatura muestran que los investigadores se han centrado principalmente en los impactos del cambio climático en elementos de los sistemas físicos y climáticos. En otras palabras, mi investigación sugiere que existe un desajuste entre las contribuciones que los investigadores del cambio climático esperan de ILK y el enfoque real de la investigación que realizan los investigadores que trabajan con pueblos indígenas y comunidades locales.

El segundo capítulo empírico utiliza una clasificación de indicadores locales de impactos del cambio climático (LICCI) para organizar las observaciones de los impactos ambientales recogidas entre los habitantes de las comunidades rurales de Sierra Nevada (España). En particular, recopilé las percepciones locales de los impactos del cambio climático percibidos por personas con una relación histórica con el medio ambiente y examiné cómo tales percepciones variaban en los entornos geográficos y los factores sociodemográficos. Realicé el trabajo de campo en 33 municipios agrupados en ocho áreas de la misma región donde entrevisté a 238 personas, entre agricultores, pastores, ganaderos, apicultores y otros informantes que realizan esas actividades para el autoconsumo. Analicé la percepción de los encuestados con respecto a los cambios en 95 indicadores de los impactos del cambio climático identificados en la literatura. El 80% de los encuestados indicó cambios en más de un tercio de los indicadores, con un promedio de 52 indicadores percibidos por cada encuestado. También encontré diferencias en la percepción entre las diferentes zonas geográficas de la región de estudio y entre las características sociodemográficas de los informantes, incluida la permanencia personal y familiar en la región y el nivel de interacción con la naturaleza.

En mi último capítulo empírico, utilizo información de la misma encuesta para abordar la relación entre el cambio climático y otros impulsores del cambio. Este capítulo proporciona un análisis más profundo de las opiniones de las comunidades locales sobre los cambios ambientales a través del análisis de redes. Muestra las interacciones entre los impactos del cambio climático percibidos

por las comunidades locales, revelando los impactos más importantes percibidos en sus sistemas socio-ecológicos y los efectos en cascada de los impactos del cambio climático en los sistemas físicos, biológicos y humanos. Los resultados del análisis de redes de los impactos percibidos del cambio climático muestran que las comunidades locales perciben los impactos en elementos de los sistemas climático y físico como los más dañinos para sus medios de vida. Pero los impactos del cambio climático en algunos componentes biológicos y humanos se percibieron como elementos clave de la red debido a su repercusión en otros elementos a través de impactos en cascada. Los encuestados percibieron el cambio climático como el principal impulsor del cambio que actúa en la región, aunque identificaron otros ocho impulsores directos e indirectos que generan cambios ambientales en la región, que a menudo se suman a las presiones del cambio climático. Los encuestados identificaron el sistema humano y luego el sistema climático como los más afectados por los efectos combinados de los diferentes impulsores del cambio.

Esta tesis contribuye a unir la ciencia occidental y la ILK en el marco del cambio climático. Los resultados sugieren que ILK debe considerarse como una fuente de conocimiento independiente y válida con su propio marco. ILK podría completar registros de datos científicos deficientes a nivel local, particularmente en lo que respecta a los impactos en los sistemas biológicos y humanos. Además, los resultados de la tesis muestran diferencias geográficas dentro de la región con respecto a los impactos del cambio climático, apoyando la idea de desarrollar planes de evaluación y adaptación a nivel local para evitar futuras inequidades por impactos distribuidos de manera desigual.

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Chapter 1.

Introduction

1.- Background. Climate change

The Earth's climate is the result of the energy balance between the incoming energy from solar radiation, and the outgoing energy from Earth. Almost half of incoming radiation is absorbed by Earth´s surface, mainly by the oceans, and the rest is reflected, but the percentage of outgoing energy from Earth is influenced by natural elements such as the presence of clouds and aerosols in the atmosphere, the percentage of land covered by deserts and masses of snow and ice, which represents the terrestrial albedo, oceanic temperatures, and greenhouse gas emissions from the volcanic activity and the movement of tectonic plates. In recent times, human activities have started to contribute to changes in this energy balance, leading to the current climate change period. For several decades, researchers have shown that current climate change is due to a combined effect of natural forces, that have produced previous climatic changes throughout the history of the Earth, and anthropogenic forces, generated by the effect of certain human activities, that supplement the effect of natural forces (IPCC, 2013). Climate change has become an urgent problem threatening life on Earth as we know it. There is irrefutable evidence that climate change has not only direct effects on the climatic system, but these impacts also have cascading effects generating noticeable impacts on physical and biological systems (Helmuth, 2009; Huey et al., 2009; IPCC, 2013; Peñuelas et al., 2013; Potts et al., 2010; Rosenzweig et al., 2008; Scheffers et al., 2016).

In this section, I review current scientific knowledge on the natural and anthropogenic forcing leading to climate change.

1.1. Natural radiative forcing

"All things are connected. Whatever befall the Earth, will befall the children of the Earth"
(American Chief Seattle)

Climate change is a process that has constantly happened throughout the course of Earth history.Geological, fossil and paleoclimate records have shown there have been periods with a higher average temperature and with atmospheric concentrations of CO_2 much higher than the current ones. For 200 million years (My), during the dinosaur's era (Mesozoic) and the beginning of the current geological era (Cenozoic), mean temperature of the Earth was higher than today (Stanley, 1999), associated with higher concentrations of CO_2. At the beginning of the Cenozoic, during the Paleocene (65 My), a period of high diversity of mammals, there were no polar ice masses and a warm and uniform climate throughout the planet prevailed. At the end of this period, there was a large increase in atmospheric CO_2, largely influenced by volcanic forces and plate tectonics releasing large amounts of methane from the oceans (Zachos et al., 2008). This produced an increase in the temperature of the ocean and increased concentrations of CO_2 in the ocean surface, increasing its acidity and generating the mass extinction of many species in the ocean while increasing the concentration of atmospheric CO_2, which reached concentrations of ~ 1000 ppm during the early Eocene period (56 My) leading to the extinction of many mammal species and expansion of most of the current mammal groups. This increase in temperature generated a warmer and more humid climate and increased precipitations that -due to the dynamics of air currents- would move towards latitudes further from the equator, generating changes of different magnitude along the different latitudes and starting to form the Antarctic ice sheet (Hollis et al., 2012; Lunt et al., 2012; Pagani et al., 2006). The cooling of the planet continued to increase until the Pliocene (2.5My), when there was a large long-term increase in global ice mass, a decrease in sea level, and a large decrease in temperatures (Fedorov et al., 2013; Herbert et al., 2010; Martínez-Garcia et al., 2011; Miller et al., 2012; Naish et al., 2009). Evidence also suggests that, throughout the Pleistocene, when the genus *Homo* appeared, there were periods of glaciation and thawing of the areas of the Earth at higher latitudes, creating different climatic conditions in different regions of the planet, depending on their latitude and orography, but CO_2 concentrations were lower than the current ones (Da et al., 2019). Overall, the periods of glaciation have been the result of orbital forcing and variations in terrestrial albedo (Bonelli et al., 2009; Ganopolski et al., 2010). The Holocene, the current epoch, began after the last interglacial period 12,000 years ago and has been characterized by relatively stable CO_2 concentrations and mild average temperature. However, natural forces have generated regional temperature differences associated with different latitudes (Cruz et al., 2009; Hély et al., 2009; Tierney et al., 2011). These conditions have remained stable within a small range of variation until the beginning of the industrial revolution (~1750), a time considered by the scientific community as the beginning from which human activities began to have a global effect on the planet, which has been defined as *Anthropocene* (Crutzen, 2006).

These previous climate change periods have been the result of natural forcing, mainly due to three natural forces: solar, orbital and volcanic forcing. Solar forcing is produced by total solar radiation produced by the sun, which can alter the percentage of ultraviolet rays that the Earth receives (Gray et al., 2009). However, studies in this regard suggest smaller changes over the 19th and 20th centuries (Lockwood and Owens, 2011; Svalgaard and Cliver, 2010). Orbital forcing refers to changes in the Earth's orbit related to its eccentricity, precession, and obliquity , reducing intensity of insolation in the northern hemisphere affecting the albedo of Earth. This fluctuation is considered the main driver for the alternation of glacial and interglacial periods (Cheng et al., 2009; Huybers, 2011; Lisiecki, 2010; Tzedakis et al., 2012; Yin and Berger, 2010). Volcanic forcing is generated by volcanic activity that produces alterations in atmospheric concentration through the addition of aerosols, which have been studied through sediments deposited in the Antarctic and Arctic ice sheets, where researchers have identified ice that is 1.5 My old (Parrenin et al., 2017). These analyses are essential to detect the influence of human activity when comparing pre-industrial volcanic periods and those produced later (Legras et al., 2010; Miller et al., 2012), which reveals that the influence of the volcanic force since the beginning of the industrial period (1750) has been 100 times less than the anthropogenic action, and therefore very insignificant (Gerlach, 2011).

Thus, along history, natural forces have generated previous periods of climate change through changes in temperatures and alteration of greenhouse gases concentrations in the atmosphere, generating all kind of impacts on ecosystems and showing regional differences. At the same time, those climate change periods has been accompanied by mass extinctions of dominant species.

1.2. Anthropogenic radiative forcing

"Climate change is the single biggest thing that humans have ever done on this planet. The one thing that needs to be bigger is our movement to stop it." (Bill McKibben)

Since the start of the industrial revolution, human activities have had a strong impact on the climatic system, including the ocean and the cryosphere. Human activities have generated other drivers of change amplifying the effect of natural forces acting on Earth's climate (Myhre et al., 2013; Rockstrom et al., 2009; Steffen et al., 2015). For example, human activities have generated changes in land uses resulting from the conversion to agricultural extensions, deforestation and afforestation, changes in the surface of ice and snow affecting the Earth's albedo, changes in the nitrogen and phosphorus cycles, changes in the water cycle, and changes in atmospheric aerosols from burning and fossil fuels. These direct impacts on ecosystems have been defined as anthropogenic forcing.

Human activities have exceeded specific thresholds generating a cascading or domino effect which indirectly contributes to climate change by changing the concentration of gases in the atmosphere through increasing the production and accumulation of greenhouse gases (Brook et al., 2008; Folke et al., 2004; Knowlton and Jackson, 2008; Micheli et al., 2005). The effect of human activities on the climatic system has been called anthropogenic climate change or anthropogenic radiative forcing (IPCC 21013). Although researchers consider the industrial revolution (~1750) the beginning of human activities repercussion at global scale, anthropogenic radiative forcing has increased more rapidly since 1970 than ever (this is sometimes called "the regime shift"). In 2011, anthropogenic radiative forcing was 43% higher than the estimation done for 2005 (IPCC AR4). In 2013, the global average atmospheric CO_2 concentration crossed 400 parts per million, a level Earth's atmosphere did not experience for at least the past 800,000 years and possibly much longer (Fischer et al., 2018; Lüthi et al., 2008). Anthropogenic forcing has not only warmed the ocean and contributed to begin to melt the cryosphere but has also led to widespread biogeochemical changes driven by the oceanic uptake of anthropogenic CO_2 from the atmosphere (ocean acidification) as has occurred previously in Earth's history (IPCC, 2013), being these changes that have defined the Anthropocene (Crutzen, 2006).

The oldest anthropogenic driver of change is land use change. Extractive and productivist human activities have modified the land cover and land use generating a direct impact on the Earth radiation through a change in the surface albedo. These activities also impact the climate through modifications in the surface roughness or changing rivers runoff and riverbeds. Land use change is happening at an unprecedented rate since 1750, with 42 to 68% of the global land surface having been transformed (by conversion to crop, pasture, or by wood harvest) during the 1700–2000 period (Hurtt et al., 2006). This transformation of land use has not been uniform throughout history, since until the middle of the 20th century, most of the change in land use had occurred in the temperate regions of the northern hemisphere (Goosse et al., 2006). Nowadays deforestation is concentrated in greater proportion along the tropics (Betts et al., 2007). Deforestation has a direct impact on the atmospheric CO_2 concentration and therefore it also contributes indirectly to albedo change with the greenhouse effect of CO_2 released (Bala et al., 2007; Pongratz et al., 2010)

Land use change produces significant regional changes and indirectly affects global mean temperature, but Findell et al (2007) showed that it generates a negligible direct impact on the global mean temperature. The greatest driver of change in human activity since the beginning of the industrial revolution has been the emission of greenhouse gases (GHG) and aerosols (IPCC, 2007; IPCC 2013; IPCC 2019). These have favored the increase in temperature, the decrease in the atmospheric concentration of ozone, and the acidification of the oceans, with countless cascading effects. Aerosol emissions have mainly been a consequence of the burning of fossil fuels, the air sector and the volatile waste generated by the chemical and petrochemical industries in the manufacturing process. After 25 years of environmental conventions and agreements on climate the first generation of aerosols was replaced, although their substitutes continue producing ozone depletion (Montzka et al., 2011). Lastly, emissions of carbon dioxide (CO_2), methane (CH_4), and Nitrous Oxide (N_2O) contribute to the destruction of ozone (Joshi and Jones, 2009; Solomon et al., 2010), to the greenhouse effect, and increasing of temperatures. The N_2O from synthetic and organic nitrogen fertilizer used in agricultural monocultures has become the third most important GHG (Davidson, 2009; Solomon et al., 2010; Syakila and Kroeze, 2011). Anthropogenic emissions of GHG and aerosols are also unequally distributed around the world, mainly located in the polluted regions in Europe, North America and Asia, although their impact is global (Fortems-Cheiney et al., 2011; Kudo et al., 2011; Wild et al., 2005; Worden et al., 2013; Yurganov et al., 2010). Similarly, aerosols from anthropogenic sources (ie, fossil and biofuel burning) are released mainly to populated regions in the North Hemisphere (Carslaw et al., 2010; Hilboll et al., 2013).

Anthropogenic drivers of change are generating impacts on the atmosphere and the Earth's climatic system, but also on the physical and biological systems of the planet. Changes observed in the hydrosphere and cryosphere allow researchers to better discern the degree of influence of the anthropogenic effect on climate change (IPCC 2013). The ocean, which acts as a thermal buffer for the planet, absorbs up to 90% of the excess heat accumulated on Earth by the greenhouse effect (Bindoff et al., 2013; Gruber et al., 2019; Rhein et al., 2013)) and has increased its surface temperature since the mid-19th century. Nevertheless, oceans and ice masses show a great delay (e.g., response or equilibrium time) in the face of sudden changes in the climate of the planet's surface. This means that current changes are consequences of the alterations previously produced in the surface, for which they will continue to evolve and change even as surface conditions stabilize (Frölicher et al., 2016; Rodgers et al., 2015). However, these systems can also change rapidly if certain thresholds are exceeded, triggering other cascading effects at a higher speed, as is happening with the rise of the sea level (Brysse et al., 2013; Church et al., 2013; Trusel et al., 2018). The global water cycle has been altered, resulting in substantial regional changes in sea surface salinity, acidity, and temperature (Caesar et al., 2018; Thornalley et al., 2018). The sequestration of a surplus of CO_2 from the atmosphere, is generating ocean acidification , endangering all species that use calcium carbonate for their shells or exoskeletons (Duarte and Krause-Jensen, 2018; Kubicek et al., 2019; Kwiatkowski et al., 2016).

The main changes in the cryosphere are the widespread retreat of glaciers, the loss of mass of the Greenland and Antarctic ice sheets, and the decrease in the extent of sea ice and snow cover in the northern hemisphere ((AMAP), 2017; Vaughan et al., 2013). Sea ice extent has declined since 1979 in all seasons of the year (Comiso et al., 2017; Onarheim et al., 2018; Stroeve and Notz, 2018), with regional differences influenced by wind trends (Hegyi and Taylor, 2018). Paleoclimate evidence shows the unprecedented rate of Arctic sea ice loss in the last 1000 years, showing a delay in the freeze-up of Arctic ice and also in snowfall accumulation on sea ice (Halfar et al., 2013; Sturm and Massom, 2016). This reduction of sea ice decreases also the albedo, creating a positive feedback (Haine and Martin, 2017). Similarly, radiative feedbacks from cloudiness are reducing sea ice surface (Morrison et al., 2018). Glaciers worldwide have experienced considerable fluctuations throughout the Holocene driven by multidecadal variations of solar and volcanic activity and by changes in atmospheric circulation. Worldwide mountain glaciers have shown a recession in the last decades, despite considerable interannual and regional variations (Medwedeff and Roe, 2017; Zemp et al., 2019). The mountain snow cover also has very strong interannual and decadal variability affected by increase in rainfall events and temperature (Kapnick and Hall, 2012; Marty et al., 2017). However, long-term in situ records are scarce in some regions of the world, particularly in high mountain of Asia, Northern Asia and South America (Rohrer et al., 2013) and the data series length is often insufficient to assess trends in these regions (Bormann et al., 2018). Finally, permafrost surface has reduced globally, and its temperature has increased in most regions since the early 1980s, with a regionally different rate of increase (Biskaborn et al., 2019). Permafrost melting also contributes to the increase of GHG, due to the methane that was trapped in the subsoil and that is being released into the atmosphere (Christensen et al., 2019; Walter Anthony et al., 2018). However, permafrost cannot easily be observed remotely and observations in situ are scarce and unevenly distributed among and within regions (Azócar et al., 2017; Bolch et al., 2019).

1.3. Current climate models, gaps and biases.

"The day science begins to study non-physical phenomena, it will make more progress in one decade than in all the previous centuries of its existence." (Nikola Tesla)

In recent decades, researchers have improved greatly in the design of climate models to be able to show the evolution of the climate during the last centuries and possible future scenarios during this century. These models are based on predictions such as our rate of GHG and aerosol emissions and the consumption of natural resources. However, the level of uncertainty in these models is still high due to the large number of factors influencing the numerous climatic variables. Aside from spatial and temporal information gaps, the main problem scientists face in predicting future scenarios is determining the degree of natural and anthropogenic influences of current changes (Bindoff et al., 2013; Cramer et al., 2014; Knutson et al., 2017)Being able to accurately determine the degree of contribution of each factor would allow a better understanding of the nature of climate change and its natural evolution (Hegerl et al., 2010). This, in turn, might result in creating policies that better control the impacts of human activities and create more effective mitigation and adaptation plans.

Nowadays, researchers are working with Earth System Models, the most comprehensive tools available for simulating past and future responses of the climate system to external forcing including biogeochemical feedbacks such as carbon, sulphur, or ozone cycles (Pongratz et al., 2018; Precious Mongwe et al., 2018). Despite the progress that has been made, the degree of uncertainty is still high as the historical data series showing anthropogenic forces do not have a longitude that allows to create extremely accurate predictions, and changes generated by human activities do not have a previous comparison in the fossil record (Allen et al., 2000; Santer et al., 2007), which makes its validation more difficult. Moreover, there are also several caveats regarding limited data from some regions (Cerezo-Mota et al., 2011; Notz et al., 2013; Thorne and Vose, 2010). Regionally important forces may be missing in some models and lack of ground-based observations are very large for some regions of the world (Bojinski et al., 2014; Miloslavich et al., 2018; Stott et al., 2010), generating different biases (Druyan et al., 2010; Mearns et al., 2012). Data gaps are fill by doing estimations with existing data in nearby areas or areas with similar climatic conditions, potentially improving precision (Harris et al., 2014), but also potentially generating uncertainties in predictions which vary according to the database used (Noake et al., 2012; Polson et al., 2013). Although these models allow us to obtain a global vision of the impacts of climate change, their degree of resolution is not sufficiently precise to show in detail the important characteristics and processes that take place on a regional scale. For this reason, regional models have begun to be developed, although these models have greater problems capturing the influence of anthropogenic forcing than global models (Hegerl et al., 2010; Stott et al., 2010), as anthropic impacts are not uniformly distributed around the globe but rather concentrated in small geographic areas, although their impacts are usually observed and calculated at a global level.

Regional models are evolving including more relationships between atmospheric variables and factors specific to the different regions such as extreme events hurricanes, river flow and discharge, sediment, soil erosion and crop yields (Pongratz et al., 2018; Precious Mongwe et al., 2018; Prudhomme and Davies, 2009). Techniques have also been developed to consider multiple climatic variables simultaneously, to preserve some physical consistency, and to include metrics related to intensities, and physical processes (Brands et al., 2011; Maraun et al., 2010; Ning et al., 2012). Current regional climate models have been improved being able to represent better precipitation extremes than global ones (Vautard et al., 2013). Despite these advancements, biases in some regions and for some climatic conditions remain (Christensen and Boberg, 2012; Knutti, 2010; Nikulin et al., 2012).

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2. Theoretical framework: Indigenous and local knowledge contribution to climate change impact research

As mentioned in the previous section, climate scientists recognize that current knowledge is not enough to predict future climate impacts with complete accuracy and that different societies and cultures will face impacts differently, depending on the intensity of impacts on each region and their resilience to overcome the consequences. International organizations and many researchers from different fields consider that Indigenous people and local communities (IPLC) could be important actors in climate change research, helping to improve our current knowledge regarding effects of climate change impacts at local levels. These communities have preserved their livelihoods during centuries and millennia, creating a close relationship with the ecosystems on which they depend, which has allowed them to develop a deep knowledge system, here referred to as Indigenous and Local Knowledge, which permits them to perceive detailed changes in their ecosystems and has been fundamental to overcome previous extreme climate events. As it has already happened in other scientific fields, ILK could contribute to improve our understanding of climate change impacts.

In this section I analyze the relationship between Western science and ILK and how it has evolved throughout history. In addition, I will delve into the current debate on the incorporation of ILK on climate change research.

2.1.- Indigenous and Local Knowledge

"*Indigenous people believe than man belongs to the World; civilized people believe that the World belongs to man." (Daniel Quinn)*

The history of humanity cannot be understood independently from of its relationship with nature. Although most people of western cultures have become estranged in their relationship with nature, many contemporary Indigenous societies still have close relationships with nature, as natural elements are fundamental in many social and spiritual aspects of these societies. In some cases, indigenous societies give natural elements a personified or divinity identity, therefore granting them the same rights or even more than other members of the community. For example, baobab trees are considered spiritual beings by some cultures in Africa, as providers of rains. They cannot even imagine to cut a baobab, moreover they offer them sacrifices of animals to attract rain (Mclean, 2010; Speranza et al., 2010). In other places, an entire mountain can be considered as sacred by the communities that surround it, like Khawa Karpo which has been conserved because of its sacredness, becoming a world reference hotspot of biodiversity (Salick et al., 2007). Many of the indigenous cultures that survive today, such as the Maori in Oceania or Native American Indians, do not understand for example that land can be bought or sold (Mead, 2016; Nadasdy, 1999). The isolated or inaccessible geographical location of some of these indigenous groups has permitted them to preserve their lifestyles almost unchanged for millennia, allowing them to better understand the functioning of the ecosystems on which they depend and being able to perceive with great precision the changes that occur in their ecosystems (Doubleday, 1993; Gadgil et al., 1993; Norgaard, 1984a; Thrupp, 1989; Turnbull, 1997).

Despite the long history of interactions between indigenous peoples and their local environment, the importance of their knowledge has not been recognized until the middle of the 20th century. During the last five centuries of history most indigenous peoples have suffered plundering of their natural resources, destruction of their cultures and genocide of their communities by western hegemonic powers (Bashford and Levine, 2010; Oesterreicher and Schmidt-Riese, 2010). The eradication of indigenous cultures increased from the 18th century with the industrial revolution and the expansion of the European colonies around the world, supported also in supposed scientific theories and with the approval of part of the scientific community of that time (Broberg and Roll-Hansen, 2005; Charles Darwin, 1871; Francis Galton, 1865; Galton, 1904; Garton, 2017). Given these antecedents, and despite the fact that anthropologists have been enormously interested in indigenous cultures throughout the 20th century, it was not until the 1970s and 1980s that part of the scientific community began to note the importance of indigenous knowledge in environmental issues (Altieri, 1983; Bell, 1979a; Brokensha et al., 1980; Howes and Chambers, 1979a; Johannes, 1978; Thrupp, 1989). This realization occurred at the same time that the scientific community warned about the drastic disappearance of many of these cultures (Gadgil, 1987; Norgaard, 1984a; Thrupp, 1989; Wavey, 1993). Researchers paying attention to indigenous peoples started to refer to their knowledge using the term indigenous knowledge (IK). Some researchers used the term indigenous technical knowledge (ITK), to refer to the techniques and skills used by these communities, realizing that this knowledge could "help" scientific knowledge to improve agricultural systems and solve "small technical" problems related to natural resource management (Bell, 1979a; Howes and Chambers, 1979a; Swift, 1979). Later, other researchers began to use the term traditional knowledge (TK), which differently than ITK emphasized that indigenous people's knowledge systems were holistic, including many more cultural and social aspects, apart from the purely technical skills and applications, that could not be separated and had to be understood and studied as a whole. This knowledge was described as much more complex knowledge system than what had been written in previous decades and including specific validation frameworks based on millennia of practice (Altieri, 1983; Brokensha et al., 1980; Freeman and Carbyn, 1988; Norgaard, 1983; Thrupp, 1989) At that time, these knowledge systems began to be described as product of co-evolution of social and ecological systems, which would have been self-regulating through processes of trial-error and natural selection over millennia until a balance between the social and the ecological system was reached (see Norgaard (1983), for the example of agroecology). The study of the relationships between social and ecological systems was also the basis for developing the concepts of social-ecological systems and common pool resources management, which have been fundamental to understand how management affect resources (Berkes, 1989; Ostrom, 1990). Some researchers, such as Thrupp (1989), have proposed the term local knowledge (LK), under the argument that the traditional knowledge of peasants in rural areas is also a valid source of knowledge at local scale (Gadgil, 1987; Norgaard, 1984a; Thrupp, 1989). In these studies, researchers began to express their concern about the importance to legitimize and empower the holders of this knowledge in decision making about matters related to the natural resources on which these communities depended.

It was in 1987, during the World Commission on Environment and Development, and later in 1992 in the Convention on Biological Diversity and the Earth Summit in Rio, of that same year, which concluded in the agreements of Agenda 21, when the importance of indigenous communities and their traditional knowledge for the conservation of biodiversity was first recognized, becoming a matter of public opinion and international recognition. The term traditional ecological knowledge was used for the first time in an IUCN publication in 1989, *Traditional ecological knowledge. A collection of essays* (Johannes, 1989), which discussed the contributions that traditional knowledge could make to science in relation to agriculture, ecology, natural resource management and sustainable development. However, the term was not defined until 1993 by Firket Berkes. In this publication, different authors presented different study cases showing the importance of TEK considered a holistic knowledge, proposing the following definition: "*TEK refers to the knowledge base acquired by indigenous and local peoples over many hundreds of years through direct contact with the environment. It includes an intimate and detailed knowledge of plants, animals, and natural phenomena, the development and use of appropriate technologies for hunting, fishing, trapping, agriculture, and forestry, and a holistic* *knowledge, or "world view" which parallels the scientific discipline of ecology*". ("*Traditional Ecological Knowledge. Concepts and cases." 1993*)

Despite the consensus about the importance and need to keep the knowledge of indigenous people and local communities alive, there was still some reluctance to widely adopt the term TEK, particularly since the term "traditional" could imply that this knowledge is something static and from the past, when in fact this knowledge is on a continuous evolution, and its functioning verified by means of a permanent validation by peers (Morrow and Hensel, 1992). The term "ecological" also found some resistance, since it is not a common term for indigenous cultures or rural communities, but rather a definition of the scientific world. Despite these different opinions, the commonly accepted definition of TEK is:

> "*TEK is a cumulative body of knowledge and beliefs, handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment. Further, TEK is an attribute of societies with historical continuity in resource use practices; by and large, these are non-industrial or less technologically advanced societies, many of them indigenous or tribal.*" (Berkes, 1993)

In other words, TEK is understood as a holistic knowledge, based on the historical observation of nature orally transmitted by its owners, from generation to generation. These knowledge systems are valid by themselves using their own frames of reference and worldviews, with a mainly qualitative understanding of natural relationships, and based on moral and spiritual rules to sustainably manage the natural resources on which they depend (Agrawal, 1995a; Berkes et al., 1995; Gadgil et al., 1993; Huntington, 1998; Nadasdy, 1999; Ohmagari and Berkes, 1997; Turnbull, 1997).

During the last decades, different authors have used the terms TEK, Local Environmental Knowledge (LEK) or Indigenous Environmental Knowledge interchangeably. In 2014, *The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services* (IPBES) proposed the term: Indigenous and Local Knowledge (ILK). The term is more inclusive regarding the knowledge of rural communities in developed countries, who might hold knowledge that is not only local and traditional, using new communication channels other than oral ones, and it is knowledge that goes beyond ecological issues, being a holistic knowledge that must be understood as part of their culture (Benyei et al., 2020; Díaz et al., 2015; Lam et al., 2020; Lyver et al., 2015; McElwee et al., 2020). Nowadays, researchers use TEK, LEK and ILK somehow interchangeably (Lam et al., 2020).

Throughout this work, I will use mainly the term Indigenous and Local Knowledge, although in chapters two and three I also use the terms TEK and LEK due to the context in which the scientific articles in which I base my review were written.

2.2.- Indigenous and Local Knowledge and Scientific Knowledge

"*We cannot solve our problems with the same thinking we used when we created them."*
(Albert Einstein)

Throughout history, western science has shown a colonialist character, incorporating and making its own the knowledge developed by other cultures (Cunningham and Williams, 1993; Nakashima et al., 2012; Turnbull, 1997). Moreover, since the scientific revolution of the 17th century, science became the hegemonic current of thought, granting itself with the authority to decide the veracity of knowledge developed by other cultures, and becoming the basis for political decision making (Ellis, 2005; Nadasdy, 1999; Smith and Sharp, 2012). It seems paradoxical that Western science, a relatively new system of knowledge, which is in continuous development and modification, has proclaimed itself the standard of truth, especially when this system of knowledge has undergone several revolutions of thought and paradigm shifts, which encountered great opposition and strong rejection by other factual powers of society as happened with the Christian religion and the Copernican revolution and Galileo Galilei. Nevertheless, the capacity for abstraction, synthesis, and quantitative analysis of western scientific knowledge has allowed to create, study and analyze frameworks on larger scales, and create theoretical models that can be extrapolated to different contexts and situations (Agrawal, 1995b; Berkes et al., 1993; Cunningham and Williams, 1993).

In general, science has underestimated ILK until the second half of the 20th century (Blurton Jones, 1976; Evans-Pritchard, 1935; Fox, 1952), considering it a primitive and backward form of knowledge, lacking rigor due to its qualitative nature and the fact that it was considered to be based on beliefs, myths and superstitions. During the 1970´s, when science had been failing for decades to stop the progressive disappearance of biodiversity and the first ecological collapses began to occur, researchers started to reconsider the traditional management of natural resources made by some IPLC. At this point, the discipline of human ecology gained scientific relevance (Human Ecology journal, vol. 1, 1972) and the scientific community began to value indigenous and traditional knowledge differently, considering that this knowledge system could contribute to solve the problems of complex systems (Brokensha et al., 1980; Levi-Strauss, 1966; Lévi-Strauss, 1963). Researchers started to warn of negative effects that was producing in the short and medium term the economic growth of the 20th century and the need to preserve and ensure the health of ecosystems for the future became an urgent problem that was put in evidence during the World Conservation Strategy (1980), which popularized the concept "sustainable development". During the next decade, researchers began to recognize benefits of the incorporation of some techniques developed by indigenous communities to agricultural production (Altieri, 1983; Bell, 1979b; Belshaw, 1979), natural resource management (Brokensha et al., 1980; Johannes, 1978; Klee, 1980; Lasserre and Ruddle, 1983; Lewis, 1985; Osherenko, 1988; Thrupp, 1989; Warren et al., 1989), biodiversity conservation (Gadgil, 1987; Johannes, 1984, 1978; McNeely and Pitt, 1985; Morauta et al., 1982; Thrupp, 1981)and sustainable development (Cohen and Uphoff, 1977; Howes, 1979; Paul, 1987; Salmen, 1987)). The concept of sustainable development was the cornerstone of the World Commission on Environment and Development (WCED) "Our Common Future" (1987), also known as the Brundtland Report, and marked the line of action of the Agenda 21 and The Earth Summit of Rio 1992. At this meeting, it was recognized that IPLC and their knowledge is fundamental for the conservation of ecosystems, and the protection and incorporation of ILK and natural resources traditional management practices are necessary to achieve sustainable development of humanity. The Convention of Biological Diversity (1992) also included, in the article 8(j), the importance of ILK in the conservation of biodiversity and the need to protect these communities and their traditional practices. Indeed, researchers clearly demonstrated that the loss of indigenous cultures throughout history has been linked to the loss of biodiversity in the areas they inhabit (Gadgil, 1987; Maffi, 2005). ILK developed by indigenous communities over centuries and millennia had enabled them to achieve sustainable management of their ecosystems (Altieri and Merrick, 1987; Anderson and Grove, 1987; Johannes, 1978; Norgaard, 1984b; Warren et al., 1989), being the main mean of natural resources management during human history (Nakashima and Krupnik, 2018; Turnbull, 1997).

Originally, researchers proposed the extraction of specific techniques developed by IPLC and its adaptation and incorporation into scientific management (Brokensha et al., 1980; Howes and Chambers, 1979b; Warren, 1991). Other researchers considered indigenous knowledge to be more complex and holistic system that could not be fragmented into independent elements but had to be understood as a whole (Agrawal, 1995b; Berkes, 1993, 1989; Dei, 1993; Levi-Strauss, 1966; Norgaard, 1984b). The scientific community recognized that the inclusion of different types of knowledge could improve our understanding and governance of environmental commons (Armitage, 2008; Berkes, 1989; Hahn et al., 2006; Olsson and Folke, 2001; Ostrom, 1990; Rathwell et al., 2015). At this time, it was also argued that the two knowledge systems, despite some similarities, also present ontological differences that hinder their communication and understanding, for which common frameworks of understanding are needed (Bohensky and Maru, 2011; Davis and Wagner, 2003; Moller et al., 2004). Similarities that might favour the connection of both knowledge systems are 1) that both of them are based on observations of natural elements that can be translated in rules, which are able to generate knowledge, 2) that both are valid for a specific geographical scale, 3) that both evolve through time modifying and creating new knowledge, and 4) that both are validated by peers (Agrawal, 1995b; Berkes, 1993; Gadgil et al., 1993; Nadasdy, 1999).

Regarding the differences, science is characterized by the compartmentalization of knowledge in different branches, in the same way that theoretical knowledge is independent of practical knowledge (science vs technology) and rational knowledge is separated from spiritual knowledge. Differently, ILK does not differentiate these elements, generating a holistic knowledge in which the human being is one element more of the ecosystems and where theory and practice are intertwined with other social, cultural and spiritual elements that maintain the resilience of IPLC's socio-ecological systems (Berkes et al., 1995; Nakashima et al., 2012; Scheffer et al., 2001). Thus, unlike ecology and other branches of western sciences, which aim to understand all the variables of nature, ILK focuses on understanding how humans should interact with other natural elements of their ecosystems and manage their natural resources in a respectful way (Berkes, 1989; Berkes et al., 1998; Fienup-Riordan, 1990; Nakashima and Marie Roué, 2002). While both knowledge systems have evolved over time, the speed of change and integration of new knowledge has been lower in the ILK due to its local and practice-based nature(Gadgil et al., 1993). In contrast with science capacity for abstraction, theoretical research, simplification and multi-space integration, ILK has great potential value because of the diachronic data on which it is based (Berkes et al., 1995). The series of historical data generated through trial and error techniques in a specific geographic location and transmitted from generation to generation over time has allowed the construction of a complex interdisciplinary knowledge system, able to describe with a high level in detail the interactions that occur between the components of their socio-ecological systems (Agrawal, 2003, 1995b; Berkes et al., 1995; Bohensky and Maru, 2011; Pierotti and Wildcat, 2000). Finally, the holistic, oral and qualitative nature of the way of transmitting the ILK has been the great challenge in front of the reductionist, quantitative and written way of thinking of the Western world.

These differences between both knowledge systems have been used to justify the impossibility of carrying out the difficult task of combining both types of knowledge (Johnson et al., 2016; Nadasdy, 1999; Turnbull, 1997). The different way of understanding the world and its interactions and therefore the different way of seeking solutions to current problems is the main goal of researchers seeking the interconnection of both knowledge systems, and the main challenge is the correct interconnection creating common frameworks of understanding in the cross-cultural negotiation, particularly due to the difficulties in accessing and correctly understanding and including the ILK perspective. It should be noted that, traditionally, researchers have focused on the extraction, collection and classification of bits of knowledge in order to preserve by publishing written articles. In this effort, researchers have focused on what they have considered to represent the ILK of certain IPLCs (Burchell et al., 2013; Foucault, 1991). However, this way of acting cannot be completely effective because it presupposes ILK as a static knowledge system, which can be captured and stored for later use, when in reality this knowledge system is under continuous evaluation and modification. Similarly, the use of written expression as a method for ILK conservation is contrary to its original nature, since the ILK is created, transmitted and preserved orally and through active practice. Therefore, this practice will contribute more to ILK documentation and storage as historical testimony than to its true conservation (Cunsolo Willox et al., 2013; Leduc, 2011, 2006) Furthermore, IPLCs do not conceive their knowledge as a compartmentalized information system, but as a “lifestyle” that cannot be used and fragmented in the same way that scientific data are treated because this practice generates the distillation and loss of that knowledge due to not being able to capture the essence that has generated it. Different authors have defined this holistic way of understanding the world as *fuzzy logic* (Berkes and Berkes, 2009), *linked spheres of knowledge* (Sillitoe and Marzano, 2009), *reflective equilibrium* (Green, 2009), or *polycentric global epistemology* (Maffie, 2009).

During the last three decades, part of the scientific community has been working to achieve a true recognition and incorporation of the ILK in the management of natural resources (Tschirhart et al., 2016) and protected areas (Brown and Kothari, 2011), biodiversity conservation (Popova, 2014; Ruheza and Kilugwe, 2012), environmental assessment and restoration of degraded ecosystems (Reed et al., 2011; Roba and Oba, 2008), environmental risk evaluation (Robinson et al., 2016; Sethi et al., 2011), mitigation and adaptation plans for environmental risks (Armitage et al., 2011), as well as IPLC representation and participation in decision-making (Reyes-García et al. 2021). Despite researchers’ efforts, the combination of these two knowledge systems has not been produced in a balanced way, and in many cases the influence of power relations dominated by western sciences is still appreciated (Clement, 2013; Mantyka-Pringle et al., 2017; Raik et al., 2008).
Despite the slow progress, the relations between both knowledge systems have evolved from dismissing ILK, to an extractive model of domain and control by scientific over traditional knowledge, and towards more cooperative and participatory models seeking true co-production of knowledge. Moreover, co-production of knowledge has been sought by different approaches such as *bridging of knowledge* (Reid, W. V., Berkes, F., Wilbanks, T., & Capistrano, 2006), *knowledge management* (Reed et al., 2011), *knowledge exchange* (Fazey et al., 2012), or *multiple evident base approach* (Tengö et al., 2014). An important consideration of this convergence of both knowledge systems is that co-production of new knowledge implies maintaining the integrity of each knowledge system, while developing settings for mutual exchange of perceptions and opinions, which generate empathy for mutual learning. The *Multiple evident base approach* allows the interconnection of multiple sources of knowledge that are validated within each specific theoretical framework for the co-production of valid and useful knowledge for all the parties involved (Tengö et al., 2014). The co-production of knowledge implies a collaborative process where knowledge is produced through interaction with people with different worldviews and sources of knowledge that are translated and assimilated by all parties, including ways to avoid power imbalances. The goal is to reach a common consensus of understanding and action through cooperative participation and mutual learning (Armitage et al., 2011; Rathwell et al., 2015; Roue and Nakashima, 2018; Tengö et al., 2017).

2.3.- Contribution of Indigenous and Local Knowledge to Climate Change research

“Not everything that counts can be counted, and not everything that can be counted counts”
(Albert Einstein)

As already discussed, climate change is generating uneven impacts around the world, and IPLC inhabiting isolated regions with lack of scientific data should be key contributors to improve current climate change knowledge. Researchers and policy makers have called for the exploration of different data sources, and particularly for locally grounded data that can complement the data series currently used to assess climate change impacts (Alexander et al., 2011; Berkes, 2009; Cramer et al., 2014; Ford et al., 2016; Rosenzweig and Neofotis, 2013a). Thus, several researchers have proposed that ILK has the potential to increase understanding of local climate change impacts (Alexander et al., 2011; Altieri and Nicholls, 2017; Barnes et al., 2013; Baul and McDonald, 2015; Chanza and De Wit, 2016; Ford et al., 2016; Hu et al., 2020; Khanal et al., 2018; Magni, 2017; Nakashima et al., 2012; Reyes-García et al., 2019; Tengö et al., 2017), with greater contributions from data-deficient regions (Belfer et al., 2017; Cai et al., 2017; Reyes-García et al., 2019; Sanchez et al., 2012; Savo et al., 2016; Wildcat, 2013). Beyond data needs, and due to the high percentage of IPLC who live in areas where the impacts of climate change are expected to be intense, there is also a growing recognition that IPLC should have the right to participate in decision-making related to their territory and empower themselves to apply their own knowledge to seek solutions (Belfer et al., 2017; Ford et al., 2016; Maldonado et al., 2016; Papillon and Rodon, 2017)

Nowadays, ILK has begun to be included into different research fields and climate change should not be different. Over time, IPLC have dealt with and overcome many environmental changes and extreme weather events, developing a knowledge system that allows them to perceive changes and adapt their daily activities to changing environmental and climatic conditions (Boillat and Berkes, 2013a; Hiwasaki et al., 2015; Turner and Spalding, 2013)). This ability turns them into first-hand witnesses of environmental changes, which might allow them to accurately report climate change impacts on their local environments (Berkes, 2017; Byg and Salick, 2009; Maldonado et al., 2016; Reyes-García et al., 2019).
Indeed, over the last decades several empirical studies have shown that IPLC perceptions of climate change impacts overlap with impacts documented in scientific records (Boillat and Berkes, 2013a; Crona et al., 2013; Fassnacht et al., 2018; Krupnik et al., 2010a; Savo et al., 2016). Some researchers have shown the overlap between local and scientific information on a diversity of topics including temperature and rainfall trends (Baird et al., 2014; Da Silva et al., 2014; Klein et al., 2014; Oyerinde et al., 2015; Rahman and Alam, 2016), species abundance (Damalas et al., 2015; Huntington et al., 2017) including fish stock declines (Brewer, 2013; Gurgiser et al., 2016), animal and plants distribution (Fossheim et al., 2015; Huntington et al., 2015), changes in migratory routes (Huntington et al., 2015; Krupnik et al., 2010b; Nakashima et al., 2012), changes in vegetation index (Gamble et al., 2010; Klein et al., 2014; Yu et al., 2010), changes in agricultural calendaires (Boillat and Berkes, 2013b; Cochran et al., 2016; Kolawole et al., 2016; Postigo, 2014), and other kinds of phenological disturbances in wild species (Armatas et al., 2016; Baul et al., 2013; Lefale, 2010; Maikhuri et al., 2018).
This overlap suggests that bridging both knowledge systems can enrich our current knowledge of climate change impacts. However, part of the climate change research community remains sceptical on the potential value of ILK in climate change studies (Rigg and Mason, 2018). Critics emphasize the epistemological differences between both knowledge systems (Ford et al., 2016; Rathwell et al., 2015), which are considered as an enormous obstacle for the creation of synergies between them (Adger et al., 2013; Orlove et al., 2010). It has also been argued that many climate change impacts are difficult to detect without the adequate scientific instruments (Howe et al., 2013b; Howe and Leiserowitz, 2013; Stone et al., 2013)and that the local nature of ILK makes its extrapolation difficult (Briggs, 2013). Finally, the different language used by scientists and IPLC to express their knowledge and the prevalence of the written form to express it, further prevents the equal participation of all the actors in the co-production of new knowledge (Conrad and Hilchey, 2011; Leduc, 2011)

Despite these critiques, researchers have started to include ILK in climate change research, vulnerability assessments, adaptation frameworks, and mitigation and action plans (Austin et al., 2017; Dazé A, 2011; Pasteur, 2011), and some intergovernmental forums like The Artic Council, have started to include the holistic perspectives of IPLC and data from their ILK in the Artic Climate Impacts Assessments (ACIA). However, ILK is not yet fully recognized as a potential data source for the collection of information on climate change impacts and attempts to bring insights from ILK into climate change research mainly focus on comparing ILK and scientific reports to validate the former (Alexander et al., 2011; Panda, 2016; Roue and Nakashima, 2018; Smith et al., 2017). In other fields of research, the scientific community, while admitting that there are ontological and epistemological differences between knowledge systems, also recognizes that ILK is valid on its own, for which many scientists have re-oriented toward the co-production of knowledge (Armitage et al., 2011; Masterson et al., 2017; Roue and Nakashima, 2018; Tengö et al., 2014; Watson and Huntington, 2014). However, in the climate change arena, many researchers continue to reproduce a domain and control model in which only science is to be considered, and knowledge produced through other systems must be validated and adapted to the scientific framework to be integrated into research projects (Cajete, 2000; Finnis et al., 2015; Gratani et al., 2011; Johnson et al., 2016; Tengö et al., 2017). Despite this general trend, a growing number of researchers advocate a respectful and inclusive communication avoiding situations of power imbalance , that allows to bridge western and ILK for the co-production of new knowledge to improve our understanding of climate change impacts (Huntington et al., 2004; Turnhout et al., 2012; Watson and Huntington, 2014; Weber and Schmidt, 2016).

In that line, researchers have shown that IPLC are able to detect changes in local weather patterns and their subsequent impacts on the physical and biological systems on which their livelihoods depend (Fernández-Llamazares et al., 2015; Orlove et al., 2000; Weatherhead et al., 2010) (see Reyes-Garcia et al. 2019 for a review). However, the intrinsic local and holistic nature of ILK continues to challenge the transferability, integration, and scalability of different sources of ILK. To increase the transferability of ILK there is a need for standardized categories able to include the qualitative and interpretative nature of the different sources of ILK, without forgetting the incommensurability of some aspects (Klenk et al., 2017; Pyhälä et al., 2016; Tengö et al., 2017). Integration of ILK from different IPLCs requires the combination of inputs from multisite place-based research. In that sense, some initiatives are trying to include ILK in climate change fora by collecting IPLC observations of climate change impacts from different sites at a regional level (King et al., 2008; Lefale, 2010; Mosites et al., 2018), and at least one research project (i.e., LICCI project (www.LICCI.eu) is attempting to develop a global approach (Reyes-García et al., 2019). The intrinsic difficulties in the scalability of local knowledge call for the creation of an interdisciplinary community including IPLC and researchers who consider both the need to effectively downscale global models to resolutions useful for local climate adaptation and the need to ensure that place-based information is effectively upscaled to global climate models (Balvanera et al., 2017; Reyes-García et al., 2019; Rosenzweig and Neofotis, 2013b; Tengö et al., 2017).

Finally, anthropologists and other social scientists have argued that socio-demographic and cultural dimensions need to be taken into account to get a complete understanding of the climate change impacts perceived (Adger et al., 2013; Howe et al., 2013a; Reyes-García et al., 2016). Although some networks of researchers are beginning to work on understanding what kind of climate change impacts are being perceived by IPLC, there is still no research corpus studying the sociodemographic and cultural factors that might influence their perception of impacts. Social scientists have argued that communities are differently affected by climate change, not only because climate change impacts are highly place-specific, but also because climate change affects communities through specific pathways largely mediated by local livelihoods and culture (O'Connor et al., 1999; Rosales and Chapman, 2015). For example, while sea-level rise is a climate-related phenomenon with potential effects on the millions of peoples living close to sea level, biophysical (e.g., magnitude of tidal influences, geologic subsidence, overall island size and relief) and socio-cultural conditions (e.g., resources to cope with sea-level rise, livelihood strategy) mediate how people perceive such change and the extent to which they will be impacted by it. There is, therefore, a very close relationship between socio-cultural and ecological or environmental factors, which requires an understanding of both in assessing perceptions of climate change impacts (Aryal et al., 2016; Fraser et al., 2011). Additionally, climate change perception, based on own experiences, plays a major role in mitigation and adaptation efforts (Armah et al., 2015), so understanding the cultural and demographic factors behind such perceptions will allow to develop more accurate adaptation measures. However, as for natural scientists, the challenge that social scientists face in their quest to understand climate change impacts on livelihoods and individual sociodemographic and cultural characteristics is the scarce amount of grounded data.

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3.- Research purpose and research questions

"If I had an hour to solve a problem, I would use the first 55 minutes determining the proper questions to ask"

(Albert Einstein)

This thesis has been developed with the aim to contribute to empower IPLC in the climate change fora, showing the importance of their knowledge in the detection of climate change impacts and other drivers of change in the global change context.

To contribute to this purpose, the specific aims of this research are:

- to analyze the state of the art of published articles studying climate change impacts perceived by IPLC around the world,
- to assess the opinion of climate change researchers about the importance of ILK in climate change studies and the possibility to include it as an equally valid source of knowledge,
- to develop methodologies aiming to bridge western science and ILK in climate change studies, while preserving ILK holistic nature and allowing the combination of ILK from different IPLC but without losing their local meaning,
- to test the methodology in a rural region of Spain for the analysis of climate change impacts perceived by inhabitants of the region,
- to analyze socio-demographic and geographic differences in the perception of climate change impacts, and
- to study the complexity of ILK through the interactions between environmental impacts generated by climate changes and other drivers of change perceived by IPLC.

I will address these specific objectives in the different empirical chapters (Chapters II-IV). Each chapter tries to achieve some of the specific objectives proposed for the research:

Chapter II: Which climate change impacts are more frequently perceived by IPLC around the world? According to the Spanish scientific community, which of climate change impacts locally perceived can better contribute to our understanding of climate change?

Chapter III: Which climate change impacts are perceived by local communities of Sierra Nevada, Spain? Which socio-demographic factors influence differences in such perception? Do geographic differences affect climate change impacts perceptions?

Chapter IV: What is the network of interactions between climate change impacts perceived by local communities of Sierra Nevada? Which climate change impacts are perceived as more impactful? How do other drivers of change interact with climate change impacts in Sierra Nevada?

4.- Research design and methods

"Before anything else, preparation is the key to success."
(Alexander Graham Bell)

This thesis has an interdisciplinary nature, being in the interphase between social and environmental sciences. Throughout the thesis, I have combined quantitative and qualitative methodologies from different disciplines, including a literature review of peer-reviewed papers, the creation and classification of ecological indicators of climate change impacts, an online survey to climate change researchers, participant observation, in-depth interviews, and face-to-face surveys with local inhabitants of Sierra Nevada. Quantitative and qualitative data were analyzed using statistical tools and social network analysis. As each empirical chapter has its own method section, here I will only explain the historical importance of the study region, the background framework project (LICCI project) and the general design of this project, and the methodologies used to carry it out.

4.1.- Study region. Sierra Nevada, Spain.

I conducted research in Sierra Nevada (Spain), the southernmost mountain range in Europe. Sierra Nevada occupies an area of more than 172,000 hectares with more than 25 peaks over 3,000 meters above sea level (masl), and the highest peak in the Iberian Peninsula, the Mulhacen (3482masl). Sierra Nevada is located southeast of the Iberian Peninsula, parallel to the Mediterranean coast (Figure 1.1). The geological origin of Sierra Nevada is from the Quaternary period, mainly formed of metamorphic hard rocks such as mica schists with a high content of graphite, quartzites, marbles and quartz-pyrites, and some areas of carbonate rocks in the lower parts (Pulido-Bosch and Sbih, 1995). From the climatological point of view, it is a semiarid region, although following the classification of Köppen-Geiger, Sierra Nevada has been classified as a cold climate with cold and dry summers (category Dsc) (Beck et al., 2018), presenting large thermal variations related to altitudinal changes (Gómez-Zotano et al., 2015). Rainfall is not very abundant and has a clear seasonal character, typical of the Mediterranean basin (Machado et al., 2011; Río et al., 2011). However, its geographical location and its high altitude make this mountain range to act as a screen, favouring the generation of precipitations. There is, however, a great pluviometry spatial irregularity, with an average annual rainfall of rain and snow of about 620 mm (l / m2), reaching 1,300 mm (l / m2) in the most north-western part and which drops to 400 mm in the easternmost sector. This annual amount of water comes largely in the form of snow that accumulates in an area of about 550 km2 of mountains above 2,000 masl (Castillo-Requena, 2000).

The Sierra Nevada geographical location and orography generates a climatic variability that allows a great diversity of ecological conditions and biotopes (Castillo Martín, 1999; Oliva and Moreno, 2008; Raso Nadal, 2011), containing 27 different types of the habitats appearing in the EU Habitat Directive (92 / 43 / EEC). Due to its latitudinal location and orography, during the retreat of the last ice age, many species from cold climates were trapped in this mountain range, which has favoured the conservation of relict species from the glacial period and the presence of many endemic species (Blanca et al., 2001; Médail and Diadema, 2009). Around 30% of the high mountain plants found (over 2500masl), are exclusive to Sierra Nevada, representing more than 80 endemic vascular plant spp. There have been catalogued more than 2,100 spp in Sierra Nevada, representing 30% of all plant species in the Iberian Peninsula, and 7% of the Mediterranean region (Figure 1.1.a). Soil characteristics and climatic contrasts, both in temperature and in rainfall, generate high levels of evapotranspiration determining the type of vegetation that can adapt to these conditions and therefore favouring endemism (Martín-García et al., 2004; Oliva et al., 2014b).

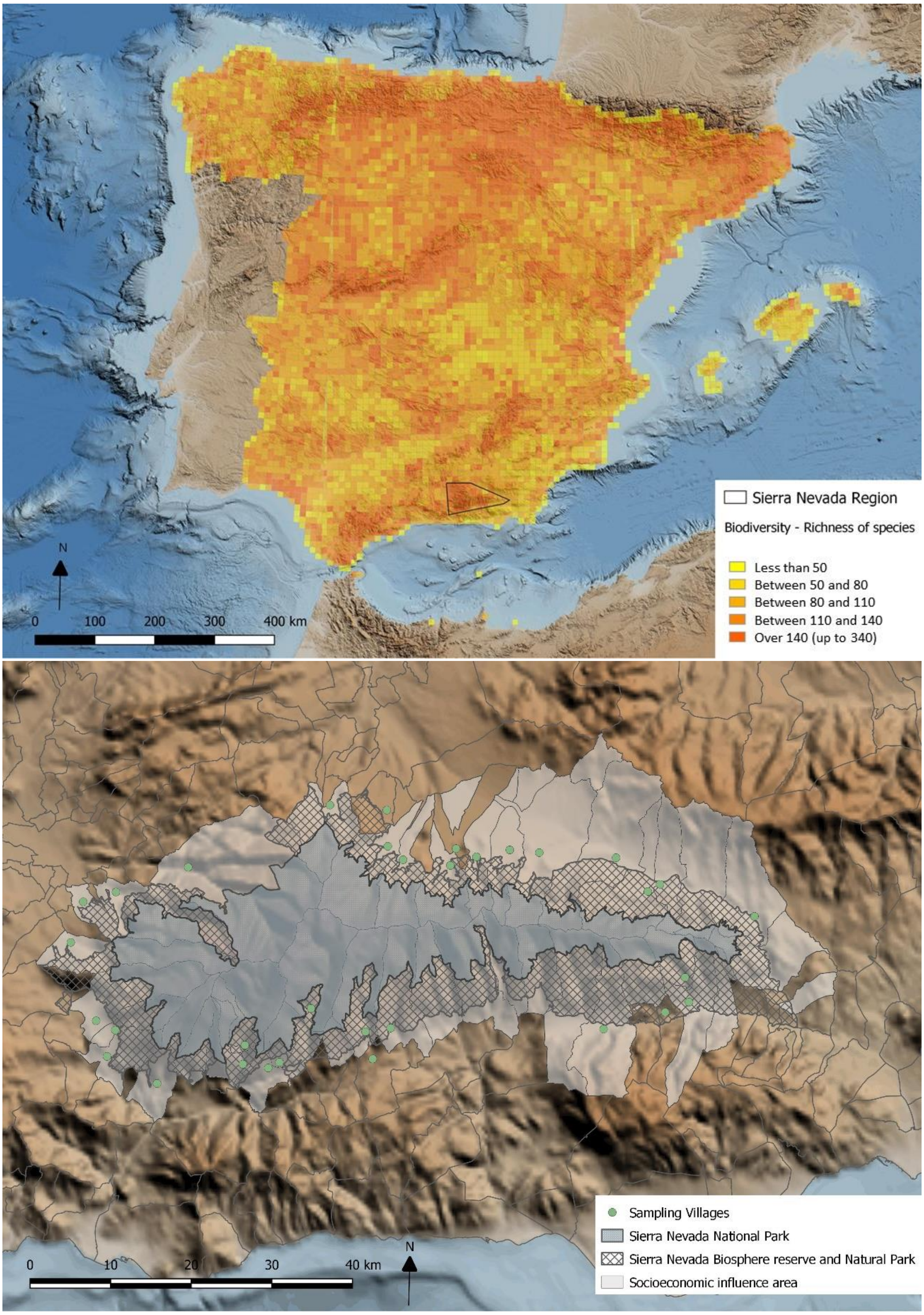

Figure 1.1. a) Map of Spain representing richness of species. Sierra Nevada's region (polygon) is one of the most important biodiversity hot spot of Spain. b) Map of the study region, Sierra Nevada. Grey area represents the National Park. Grilled area represents the Natural park and the Biosphere reserve. The light area represents the socioeconomic influence area. Green dots are the sampling villages of the field work (n=33).

The main natural ecosystems are composed by Holm oak (*Quercus ilex*), Pyrenean oaks (*Quercus pyrenaica*) and Scot pine forests (*Pinus sylvestris var. nevadensis)* in low and middle altitudes, and mix of high-mountain scrublands, mainly *Juniperus communis*, and herbaceous plants up to 2500 m asl. Due to its natural characteristics and the influence of human presence over the last thousand years which has favoured its high biodiversity, Sierra Nevada has been considered the most important biodiversity hotspot in the Mediterranean basin (Blanca et al., 2001, 1998; Cañadas et al., 2014; Pérez-Luque et al., 2015). Its singular ecological and geological characteristics have granted its recognition as a natural park (1989) and national park (1999). Moreover, the importance of the sustainable use of the environment by local communities was recognized by the UNESCO Man and Biosphere program (MAB) with the creation of a Biosphere Reserve in 1986. In 2007 Sierra Nevada was also designated as a Global Change Observatory due to its singularity to study the effects of climate and other drivers of change, and as Sierra Nevada Natural Space (SNNS) when developed an integrated plan including the natural and national park (Zamora et al., 2016).

4.2- Local Communities and Sierra Nevada, developing of Local Knowledge

Like in many other areas of the Mediterranean basin, human settlement in Sierra Nevada dates back to the Neolithic era (Sánchez-Hita, 2007), propitiating the co-evolution of social and ecological systems over millennia (Blondel, 2006). Archaeological remains have shown that this region was inhabited by Phoenician and Roman settlements (José Luis López Castro, 1995; Medina, 2000). Later, during the Arab period, from the 8th century up to the late 15th century, local communities developed a sophisticated water harvesting and irrigation system that allowed a more efficient use of resources in the area (Fernández Escalante et al., 2006; Martín Civantos, 2011; Roldán and Moreno, 2010). This runoff water harvesting technique captures surficial water and groundwater and distributes it over growing areas through irrigation channels or canals (Jódar et al., 2017a; Kamash, 2012; Martos-Rosillo et al., 2019; Pulido-Bosch and Sbih, 1995; Ruiz Ruiz and Martín Civantos, 2017). Other IPLCs around the world, particularly in semi-arid regions where irrigation water is not regularly available, have also developed harvesting of runoff water systems, such as “jessur” in Tunisia, “tabia” in Libya, “hafaer” in Jordan and Sudan, “qanats” in Iran, “sabeans” and “marib” in Yemen or “cheo-ozihi”, “zabo” and “ghul” in the Himalayas. The technique traditionally used in Sierra Nevada, called “acequias” (from Arabic “as-s ¯aqiya”, meaning a water conduit or irrigation canal) consisted in tapping water from hill slopes in length from 1 to 15 km. Such technique can also be found in northern Mexico and other areas of South America (Fernald et al., 2015; Salazar and Casanova, 2011). Water harvested through these techniques is then used for the irrigation of crops, pastures, and trees, and for human and livestock consumption. These water harvesting techniques form part of the local culture and cultural frames, being the pivotal element of their socio-ecological systems.

In Sierra Nevada, water is also the conductive element that integrates the socio-ecological systems. Runoff water harvesting techniques were used to collect melting and rainfall water, to derive water from rivers and ephemeral streams, and to extract groundwater by means of qanats and wells to irrigate water deficient areas. Like in other high-mountain regions, the hydrologic regime of rivers and temporal rivulets depends on the storage of water in the ground and snow on the highlands returning to river flows in the melting periods (Staudinger et al., 2017). Thus, communities who developed this water harvesting method needed to understand the hydrological functioning of high-mountain watersheds (Burn et al., 2008; Welch and Allen, 2012), which is directly related with the meteorological variability of the territory (López-Moreno et al., 2014). Arab communities established a water management system that consisted of deriving the meltwater from the headwaters of the mountain streams and rivers and recharging it halfway down the terraced hillside through long handcrafted channels excavated directly in the ground, and locally known as *"acequias de careo"* (Martos-Rosillo et al., 2019; Pulido-Bosch and Sbih, 1995). These special *acequias* are located high in the mountains near the peaks. They are excavated through the eroded zone of the hard metamorphic rocks with the least possible slope, to avoid soil erosion and to favour water infiltration in specific areas called "simas", for its subsequent appearance in the lower part of the slopes (Fernández Escalante et al., 2006; Jódar et al., 2017b; Martos-Rosillo et al., 2019; Pulido-Bosch and Sbih, 1995). The *acequias de careo*, constitute the oldest managed aquifer recharge system in Europe (Martos-Rosillo et al., 2019). As the local inhabitants say, "*By sowing water through the careos, we can use the same water several times along the slopes, because it infiltrates in the subsoil to reappear again below"*.

Sierra Nevada irrigation system does not only provide recharge, but it also favors many ecological functions allowing the maintenance of ecosystem health. The infiltration of water into the soil maintains soil moisture allowing a diverse and abundant soil biota, improves water quality by filtering fertilizers, pesticides, and other organic contaminants, favors soil conservation, reduces erosion produced by torrential waters and favors the deposition of sediments in the upper parts of river courses (Fernández Escalante et al., 2006; Jódar et al., 2017b; Martos-Rosillo et al., 2019; Pulido-Bosch and Sbih, 1995; Roldán and Moreno, 2010). The system also favors the increase in animal and plant biodiversity, both aquatic and riparian, creating new ecological niches, it increases the production and diversity of pastures on the slopes, it acts as an ecological corridor and refuge for certain species and it generates a source of water and nutrients in normally deficient biotopes (Guzmán Álvarez et al., 2010; Martos Rosillo et al., 2018).

Additionally, the system provides water to the communities that live in the middle of the slopes and on the valley farms during the summer, in addition to re-feeding the flow of mountain rivers in lower reaches with water from these sources when there is no precipitation and snow on the peaks has completely melted. During rainy months, which coincide with the melting season, when the flow of the rivers is maximum, the water is diverted through the irrigation channels to the zones of artificial recharge that will keep the water table close to the surface favoring the appearance of temporary springs and conserving the flow of permanent sources. The *acequias de careo* slowly descend the slopes of the valleys as they enter the cultivation areas located at lower elevations, at which time they branch into smaller irrigation ditches to distribute the water through the different agricultural plots of the slopes of the valleys. Some of these channels cover more than 15 km from the area in which they capture water up to the aquifer recharge zone and there are currently more than 700 km throughout the entire Sierra Nevada (Martos-Rosillo et al., 2019)

Water in Sierra Nevada is managed by informal institutions represented by the irrigation communities, made up of the people of each town who benefit from the water that is transported from the mountains by each irrigation ditch for their crops or for pastures. The irrigation communities in Sierra Nevada have a historical character: the first written statutes of some of them date from the 13th century (Espinar, 1989). These irrigation communities are responsible for the maintenance, repair and annual cleaning of the sediments accumulated in each irrigation ditch, which must be carried out by the members of each community. Community members should also decide how the water is distributed among them. Each community of irrigators, based on the ILK accumulated over the centuries, has developed its own water distribution and measurement system, which is almost adapted to each valley and ravine of Sierra Nevada. Thus, some communities distribute the water (batches) every week, others every 10 days and others every 15. In the same way, the different communities distribute the volume of water in minutes, "parás"(stops), "fanegas" (bushels, or i.e., the volume of water to irrigate a bushel of land), "celemines" (little bushels, or i.e., volume of water to irrigate one eighth of a bushel of land, and it represents seven and a half minutes of water), "obrás" (i.e., the volume of water to irrigate the surface of a piece of land that can be carved in a full labour day with a plow with two oxen), or "marjales" (marshes, i.e., the volume of water required to irrigate the surface of the Lions´ courtyard of the Alhambra Palace in Granada), among others (Guzmán Álvarez, 2010). This distribution system, despite not having standardized units of measurement, was developed with a high degree of precision, taking into account several aspects as the time water takes to travel from one agricultural plot to the next, the volume of water that infiltrates the soil and cannot be used for irrigation, or the volume of water lost through evaporation and therefore the difference between watering during the day or at night, among many others. This level of detail of the rules that govern the informal institutions that maintain the socio-ecological systems of Sierra Nevada represents the level of understanding of their social-ecological systems.

The close relationship developed between Sierra Nevada communities and their ecosystems through their ILK, and the current scientific acknowledgement of the importance of ILK of IPLC in climate change studies indicate that the region is a good research site to study local perceptions of the impacts generated by climate change and other drivers of change.

4.3.- Sierra Nevada, climate change and other drivers of change

"Tres cosas hay en Granada que duran el año todo, nieve en la Sierra Nevada, arrebol para la cara, y en la calle Elvira lodo." *(Unknown. Popular proverb)*

Mountains are regions with special characteristics and climate change impacts in mountains might have repercussions beyond them (Fox and Funnell, 2004; Thomson and Rogers, 2014; Viviroli et al., 2007; Zemp et al., 2019). Like in other mountain regions, climate change is generating several impacts in Sierra Nevada. In particular, and like the entire Mediterranean basin, Sierra Nevada has experienced a great variation in rainfall in the second half of the 20th century (Machado et al., 2011; Oliva et al., 2014a). Since the 1970s, rainfall trends have shown variation in temporal distribution, in amount of average rainfall and in intensity (Zamora et al., 2016). This variation has been produced by changes in atmospheric pressures generated by the Mediterranean and the Atlantic Ocean (Machado et al., 2011), which has resulted in the decrease of mean rainfall amount mainly during autumn and winter and the accentuation of drought periods during summer (Ruiz Sinoga et al., 2011). Until the middle of the 20th century, Sierra Nevada had a permanent snow cover on the summits, which represented the glaciers located further south on the European continent. During the second half of the 20th century, these glaciers were reduced to small snowfields located on the north face of the highest peaks, which preserved permafrost areas since the last glacial period (Gómez-Ortiz et al., 2015; Oliva et al., 2018). However, the decrease in rainfall and the increase in the average temperature, and especially the minimum temperature (Zamora et al., 2017), have changed the thermic conditions of the soil, resulting in the disappearance of permafrost in the peaks of Sierra Nevada (Gómez-Ortiz et al., 2012; Oliva et al., 2016). This reduction in the amount and duration of ice and snow cover (Pérez-Palazón et al., 2015) has had an impact on the entire hydrological system of the ecosystems of Sierra Nevada and the surrounding territories (Bonet et al., 2013; García-Ruiz et al., 2011; Jódar et al., 2017a). The impacts of these changes have been observed in high mountain lagoons, which have increased their surface temperature and reduced their volume (Morales-Baquero et al., 2013; Pérez-Martínez et al., 2007), some of them completely drying out during summers (García-Alix et al., 2017). In the same way, changes in atmospheric currents have favored the increase of dust deposits from the Sahara, increasing the concentrations of diatoms and masses of algae in the lagoons, favouring their eutrophication (Jiménez et al., 2018).

The reduction in rainfall and the duration of snow cover on the peaks is having a very negative effect on all endemic xerophytic vegetation and high mountain pastures, which represent a large part of Sierra Nevada endemic and relict species (Blanca et al., 2001; Zamora et al., 2017). These

changes have also impacted flora and fauna resulting in an up-slope range shift of insects (Menéndez et al., 2014). This altitudinal shift is leading to the extinction of many of these species particularly when they reach their upper elevation limits (Habel et al., 2010). In fact, in Sierra Nevada, this situation has endangered relic interspecific interactions from the last glacial period, such as the one between the butterfly Agriades zullichi and its larval foodplant Androsace vitaliana nevadensis (Barea-Azcón et al., 2014). Populations of aquatic macroinvertebrates have changed, moving towards higher elevations, increasing the diversity in the upper reaches of the rivers as the surface temperature of water has increased (Garcia-Raventós et al., 2017; Sáinz-Bariáin et al., 2016). During the last decades, 89% of monitored insect spp like ants, dung beetles or butterflies Apollo have increased their upper distribution limits between 200 and 400 meters and more than 84% have also increased their lower distribution. Vertebrate species are showing the same trend: alpine species are becoming less abundant while generalist and lowland species are spreading along the mountain (Zamora et al., 2017) Bird species composition is changing and the abundance of some spp has decreased during last decade (Zamora and Barea-Azcón, 2015). The composition and distribution of flora is also shifting (Fernández Calzado et al., 2012; Mesa and Calzado, 2010; Pauli et al., 2012). Pinus sylvestris and Juniperus communis are diminishing in low-elevation areas and increasing their upper distribution, mainly in the southernmost edge of the mountain region (Garcia et al., 2000; Matías and Jump, 2015). Alpine vegetation is declining and disappearing while scrubs and low-elevation species are increasing the vegetation cover in up-lands (Gottfried et al., 2012).
Climate change is not the only driver of change acting in Sierra Nevada, which is also affected by other direct and indirect drivers of change, which often increase climate change impacts. For instance, during the 19th and beginning of the 20th century, Sierra Nevada suffered a great deforestation due to mining activities (García-Pulido, 2014). This situation was accentuated with the Spanish civil war (1936 – 1939) and the intense droughts and lower agricultural production of the following years. Furthermore, the orography of Sierra Nevada made it difficult to incorporate technological improvements in agriculture and livestock. This situation generated poverty leading to the rural exodus of more than 25% of the total population of Sierra Nevada between the 1960s and 1990s. In some areas, rural exodus has led to a decrease of 70% of the inhabitants (Prados Velasco and Valle Ramos, 2010). During that period, the government created reforestation campaigns to stop soil erosion and to compensate for the lack of job opportunities in the region. Finally, the declaration of a natural park and national park in the area led to restrictions in the livestock load allowed in the region and the surface area designated for agricultural use. As a consequence of these changes, the forest area, and specifically the coniferous formations which encompass pine forests, has spread its surface more than 60%, and the cultivation surface has been reduced from 17.8% to 4.7% of the region, that nowadays is included into the protected area, during the second half of the 20th century, affecting also to the pasture surface (Gutiérrez-Hernández et al., 2016; Zamora et al., 2016).Besides, increased herbivory pressure also affect plant species growth and reproduction (Herrero et al., 2012; Zamora et al., 2001; Zamora and Matías, 2014), generating heterogeneous effects across areas and species. Finally, during the 1960s, a ski resort was built in the higher peaks (Gómez-ortiz and Oliva, 2013), which has greatly increased its surface and number of artificial snow cannons since its creation.

All these changes have generated a profound transformation in the socio-ecological systems of Sierra Nevada. The rural exodus, together with the abandonment of the primary sector to promote the service sector, has greatly weakened the social structure and, therefore, the importance of informal institutions, such as irrigation communities. As the number of people dedicated to agriculture and livestock is reduced, the maintenance of irrigation infrastructures is increasingly complicated, being in many cases abandoned. However, this abandonment does not only affect the availability of water for irrigation, but also the amount of water available for human consumption, the humidity of the soil, the volume of infiltration, the recharge of the aquifers, the depth of the water table, the flow of rivers and streams, the number of active springs during the summer and the air humidity. In the same way, it will affect the abundance, distribution and health of wild flora and fauna. In other words, climate change impacts in Sierra Nevada cannot be understood in isolation, as they are aggravated by the simultaneous effects of other drivers of change, which act unevenly in the territory, generating different impacts in different areas.

4.4. Local Indicators of Climate Change Impacts (LICCI) and Multiple Evidence Base (MEB) approach

This research was conducted within the framework of the ERC project: "LICCI – Local Indicators of Climate Change Impacts: the contribution of local knowledge to climate change research" (www.licci.eu). The LICCI project aims to bring ILK to climate change research, creating an interdisciplinary network of collaborators, composed by IPLC and climate change researchers, and encouraging the participation of IPLC on international, national, and local negotiations and decisions related to climate change. The LICCI project includes almost fifty field sites around the world where researchers are working with IPLC identifying climate change impacts detected by those communities. My thesis has been the pilot project from which working protocols of the LICCI project have been developed. These tools include protocols for interaction with collaborating IPLCs, methodologies for data collection (Reyes-García et al., 2020), and a system for the identification and classification of climate change impacts perceived by IPLC solving the handicaps of transferability, integration and scalability inherent to the holistic nature of ILK (Reyes-García et al., 2019).

To bridge different sources of knowledge for the co-production of new knowledge, the LICCI project and this thesis, adopt the multiple evidence base (MEB) approach (Tengö et al., 2017, 2014). This conceptualization encourages the creation of synergies between different sources of knowledge, mutually benefiting from the exchange of knowledge that will allow bridging different knowledge systems by integration, cross-fertilization, and co-production of knowledge. The MEB approach understands knowledge integration and cross-fertilization as respectful processes avoiding power imbalance among different knowledge systems, legitimating each knowledge by itself within its own context, and validating within its frames of reference (Agrawal, 1995; Armitage, 2008; Berkes, 2012, 2009; Johnson et al., 2016; Nadasdy, 1999; Nakashima et al., 2012). The co-production of knowledge can be observed in many examples of co-management (Armitage et al., 2011; Berkes, 2009; Plummer et al., 2012), community-based management (Banks et al., 2003; Velempini et al., 2016), and participatory natural resource monitoring (Austin et al., 2017; Brammer et al., 2016; Danielsen et al., 2007; Reed et al., 2005; Wiseman and Bardsley, 2016).

The MEB approach considers that bridging of knowledge should start with the mutual definition of the problem, identifying the problem by experts in the issue representing different sources of knowledge, institutions, policy makers and stakeholders involved. This myriad of actors must also be in communication throughout all phases of knowledge generation (Pohl et al., 2010; Rist et al., 2011; Shirk et al., 2012). Bridging of knowledge requires different phases that representatives of each source of knowledge should do to allow mutual understanding; it includes mobilization, translation, negotiation, synthesis, and application (Figure 1.2.). Mobilization requires that each knowledge is expressed in a way that can be shared among other people. Translation means doing each knowledge understandable by all the parties to be able to compare different perspectives by the implied actors. Negotiation involves comparison of perspectives looking for synergies and contradictions across knowledge systems, identifying conflicts and trade-off among knowledges. Synthesis implies to define or create common knowledge, recognized by all the actors, that preserves the integrity of each knowledge system within each framework of reference. Application involves uses of common knowledges by the different parties for decision making at international, national and local scales, with the aim to create feedback compatible with each knowledge system. Finally, results from application of the new common knowledge should be analyzed and evaluated by the different knowledge comparing the assessments looking for new gaps and inconsistencies among knowledge systems (Tengö et al., 2017).

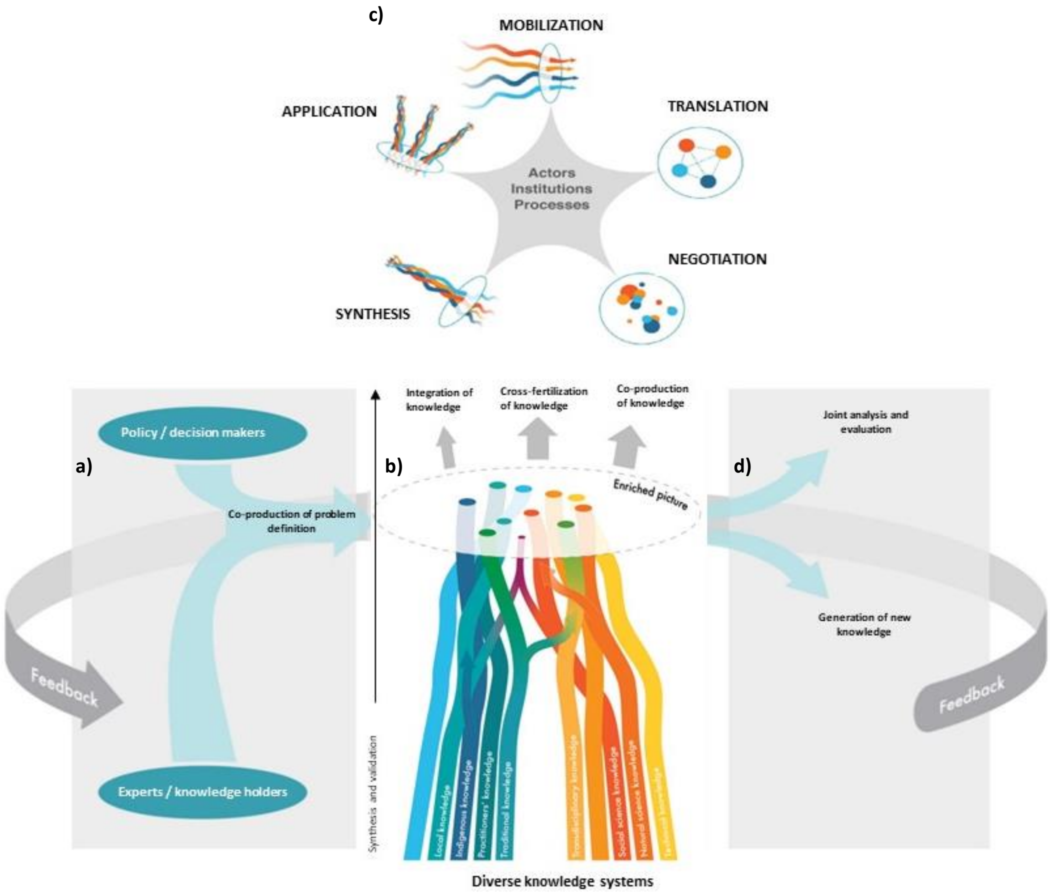

Figure 1.2. Conceptual framework of the multi-evidence base approach (MEB) indicating the process of generation of common knowledge, which implies a) definition of the problem and objectives together; b) bridging different sources of knowledge by integration, cross-fertilization and co-production; c) defining common knowledge by all parties involved by mobilization, translation, negotiation, synthesis and application; and d) analysing and evaluating results after applying the common knowledge. Adapted from Tengö et al. 2014, and 2017.

4.5. Data collection, fieldwork and research methodologies

Throughout this thesis, I have applied an interdisciplinary set of research methodologies from social and natural sciences to cover the full spectrum of perspectives about my research topic.

First, I conducted a systematic literature review of scientific publications following the rules of being *replicable*, *transparent*, *objective*, *unbiased* and *rigorous* by selecting specific key words directly related with my research interest (Boell and Cecez-Kecmanovic, 2015; Oates et al., 2012). Literature review is a method broadly used in research (Hart, 2018) and currently it constitutes a basic first step in interdisciplinary and mix-methods research which combines qualitative and quantitative methodologies (Azorín and Cameron, 2010). Specifically, I conducted a literature review in *Scopus* and *Web od Science* search engines to have a more complete overview of my research interest, climate change impacts, IPLC and ILK.

Next, to assess the opinion of climate change researchers and thus include the scientific perspective in relation to local knowledge of climate change, during the first steps of the project, I created a web-survey to address to researchers. Web-surveys are a widely used resource nowadays due to their ability to collect large amounts of data in a short time and with a low resource investment (Duffy et al., 2005; Kellner, 2004). Although numerous authors have demonstrated the potential problems associated with web-surveys addressed to the general public (Duffy and Smith, 2005; Liu and Wronski, 2018; Meade and Craig, 2012; Milton et al., 2017), they seem to be more accurate when addressed towards a specific sector of society sensitized with the subject of the survey (Duffy and Smith, 2005; Paas and Morren, 2018; Shih and Xitao, 2008).

During fieldwork, I also used a combination of qualitative and quantitative methodologies to gather field work data. Thus, during two periods of field work, I conducted in-depth and semi-structured interviews to the local population, and I developed and conducted questionnaires in the same communities. In-depth interviews is a classic methodology from social sciences (Legard et al., 2013; Roulston et al., 2003), that allows respondents to have the opportunity to discuss issues that were not originally included in the interview topics (Huntington, 1998; Roulston et al., 2003), giving researchers a more complete overview of the matter and the opportunity to understand better the different perspectives related with the research topic.

Information from the literature review, web-surveys and interviews was combined to develop the questionnaire that I conducted to the local population of Sierra Nevada. The use of questionnaires to assess the population's perception of environmental problems (Calvet-Mir et al., 2012; Martín-López et al., 2012; Oteros-Rozas et al., 2013; Shively, 2011) and study their ILK (Gallois et al., 2017; Reyes-García et al., 2016) is a technique widely used in research, and currently also to study the perception of impacts generated by climate change (Camacho Guerreiro et al., 2016; He and Richards, 2015; Speranza et al., 2010; Wang and Cao, 2015).

Finally, to analyse data from the questionnaires, I conducted statistical analysis and applied a network analysis. Social network analysis (SNA) is a methodology that allows to represent social relationships between people, although it also has been broadly applied in ecological studies (Fath et al., 2007; Ulanowicz, 2004), analysis of social-ecological systems´ structure [127–129], transmission of ILK and knowledge exchange (Calvet-Mir and Salpeteur, 2016; Díaz-Reviriego et al., 2016), and natural resources co-management (Bodin et al., 2006; Salpeteur et al., 2017). Some researchers have also applied network analysis to assess the simultaneous effect of multiple drivers of change on ecosystems (Rocha et al., 2015).

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5.- The roadmap of the thesis

This doctoral thesis is comprised by five chapters: this first introductory chapter, three chapters that correspond to scientific articles with the empirical data, and a final chapter with the conclusions of the thesis. The three articles have been developed in a complementary way, using the results of the first one to develop sections of the methodology of the following articles In the annexes, I have included another two articles directly related with the research and the study area in which I contributed substantially.

In this first chapter, I have presented the background of this research, including the causes, evolution and current state of climate change impacts and the importance of indigenous and local knowledge in climate change research. In this chapter, I have also presented the aim of the research and the main research questions. Finally, I have presented the research design, the framework and the methodologies applied.

The second chapter reports results from a literature review of scientific papers documenting first-hand observations of climate change impacts perceived by IPLC with ILK in the climatic, physical, biological, and human systems of their social-ecological systems. Following Reyes-García et al (2016), I analyzed 308 scientific articles published until December 2016, selecting 135 of them to collect verbatim reports of observations of climate change impacts. These observations were grouped together when referring to the same phenomenon (e.g., extremely hot days and hot temperatures are extremes nowadays) in Local Indicators of Climate Change Impacts (LICCI) (Reyes-Garcia et al., 2016; Reyes-García et al., 2019). The LICCI classification followed a hierarchical structure of four levels composed by systems, sub-systems, impacted elements, and LICCIs, which represent the lower level. The classification of local indicators was designed without losing its local meaning or changing the frameworks on which they were created. For this reason, indicators such as *Change in temperature during the day* or *Change in the intensity of fog* can be found in the classification, which are not as accurate as those obtained by scientific measurement devices. In the same way, the classification also integrated indicators that reflect the holistic nature of ILK respecting their own reference systems, such as *Changes in the predictability of rainfall*, *Changes in the behaviour of the animals* (regardless of phenological changes) or *changes in the sense of identity or spirituality* of the IPLC. The complete classification of the indicators can be found in the first annexed document. To bridge this information with scientific knowledge, I created a web-survey with the list of indicators of climate change impacts and requested opinions from climate change researchers on the importance of ILK in climate change studies. I used this information to assess which would be the research areas in which the co-production of knowledge could be generated more easily (first chapter of results). The survey was opened for eight months and three reminders were sent to the potential participants (n = 2100) to encourage them to participate. After that period, I closed the survey with 8% of participation (191 researchers), being a similar result as obtained by researchers working on participatory processes and citizen participation (Masters et al., 2016; Wiggins et al., 2011).

The third chapter uses data collected during fieldwork. I conducted a 1-month fieldwork session during the summer of 2017, when I conducted 20 in-depth interviews with elderly farmers, shepherds, ranchers, and beekeepers from rural communities of Sierra Nevada. Informants had an extensive knowledge of the region and interviews focused on the type of climate change impacts perceived in the region since their youth. However, being in-depth interview, respondents also had the opportunity to discuss other issues, like other environmental impacts perceived in the region. Through these interviews, I verified that local population of Sierra Nevada was perceiving many of the impacts found in the literature review. These in-depth interviews allowed me to learn more about the local reality of the communities of Sierra Nevada and to establish initial contacts for the future development of the project. Information from the semi-structured interviews and results from the web surveys were the basis to develop the questionnaire applied during fieldwork. Before starting the fieldwork, another ten interviews were conducted and scientific literature about the region was contrasted to select the final list of local indicators of climate change impacts to be included in the survey.

Field data for the empirical chapters of my thesis was collected through questionnaires. For eight months, from May to December of 2018, I conducted questionnaires to the local population of Sierra Nevada (n = 238) dedicated to agricultural and pastoral activities as a main or secondary profession, and with a permanence in the area of more than 25 years. The questionnaires collected data about climate change impacts perceived in their territory. In order to study the geographical differences in the intensity of the impacts of climate change generated at local scale (IPCC, 2013; Rosenzweig and Neofotis, 2013), I conducted field work in 33 municipalities divided into eight different areas around Sierra Nevada, my study region. In order to contribute to fill the gaps that exist in the study of sociodemographic and cultural factors that influence the perception of the impacts of climate change (Adger et al., 2013; Howe et al., 2013; Reyes-García et al., 2016), I studied the sociodemographic variables that patterned differences in perceptions. I also explored another alternative way to study climate change impacts through ILK. In collaboration with other researchers, I studied perception of climate change impacts through climatic proverbs assessing the accuracy of those proverbs compared with the current climatic conditions (Second annexed document).

The fourth chapter, which corresponds to the third empirical chapter, was designed to analyse the complexity of ILK held by local communities of Sierra Nevada. I analyzed interactions between climate change impacts perceived by interviewees and the simultaneous effect generated by other drivers of change in the region. I applied social network analysis to study this type of interactions between impact and impacts and drivers, looking for those impacts acting with greater intensity in the region, and those climate change impacts having a special position in the networks due to the repercussion of its cascading effects. This article compares the main impacts detected by local population considering only climate change and including all drivers of change acting in the region. The study analyses differences in the perception of local population directly related with agropastoral professions and people indirectly related, as a secondary activity or self-consumption.

The final chapter presents the main conclusions of the previous chapters and discusses the main contributions of this thesis in the methodological and practical application of such methodologies. I also address the main challenges and caveats of the thesis and propose improvements for future research.

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- Results -

Chapter II.

Including indigenous and local knowledge in climate research: an assessment of the opinion of Spanish climate change researchers

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Including Indigenous and local knowledge in climate research. An assessment of the opinion of Spanish climate change researchers.

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Abstract:

Researchers have documented that observations of climate change impacts reported by indigenous peoples and local communities coincide with scientific measurements of such impacts. However, insights from indigenous and local knowledge are not yet completely included in international climate change research and policy fora. In this article, we compare observations of climate change impacts detected by indigenous peoples and local communities from around the world and collected through a literature review (n = 198 case studies) with climate scientists' opinions on the relevance of such information for climate change research. Scientists' opinions were collected through a web survey among climate change researchers from universities and research centres in Spain (n = 191). In the survey, we asked about the need to collect local-level data regarding 68 different groups of indicators of climate change impacts to improve the current knowledge and about the feasibility of using indigenous and local knowledge in climate change studies. Results show consensus on the need to continue collecting local-level data from all groups of indicators to get a better understanding of climate change impacts, particularly on impacts on the biological system. However, while scientists of our study considered that indigenous and local knowledge could mostly contribute to detect climate change impacts on the biological and socioeconomic systems, the literature review shows that information on impacts on these systems is rarely collected; researchers instead have mostly documented the impacts on the climatic and physical systems reported by indigenous and local knowledge.

Keywords: Indigenous and Local Knowledge, local indicators of climate change impacts, web survey, scientists' opinion.

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1. Introduction

Climate change impacts are becoming evident in all the Earth's ecosystems (Allen et al. 2010; Cardinale et al. 2012; Hoegh-Guldberg & Bruno 2010) with measurable impacts on the physical and biological systems (Helmuth, 2009; Huey et al. 2009; Peñuelas et al. 2013; Potts et al. 2010; Rosenzweig et al. 2008; Scheffers et al. 2016). Inevitably, such impacts also affect the socio-economic and cultural systems of local communities with direct dependence on the environment (Adger et al. 2013; Wang & Cao 2015).

Most of the current knowledge on future climate change impacts transcending to the public opinion and decision makers comes from research on the natural sciences and from the use of predictive models relying on mathematical representations of large-scale records of weather variables combined with gas emission scenarios. These models describe future climate changes at global or regional levels, even in data deficient regions for which interpolation of adjacent data is used (Harris et al. 2014). While recent improvements of these tools (Pierce et al. 2009; Rummukainen 2010) have greatly expanded our understanding of climate change (Maraun et al. 2010), the scientific community recognizes that these models are still too imprecise to detect impacts produced at the local scale (Fernández-Llamazares et al. 2017; Stott et al. 2010). The mismatch between the scale at which impacts are modelled and the actual scale at which local communities will have to overcome climate change impacts inhibits local actors to get an accurate prevision of the impacts that will affect their environment and livelihood (Kolawole et al. 2016; Xu et al. 2009). For this reason, researchers and policy makers have called for the exploration of different data sources and particularly for locally grounded data that can complement the data series currently used to assess climate change impacts (Alexander et al. 2011; Berkes 2009; Ford et al. 2016; IPCC 2014; Rosenzweig & Neofotis 2013).

Along this line, a growing number of scientists argue that Indigenous and Local Knowledge (ILK) holds the potential to improve our understanding of climate change impacts and thus help in the quest to adapt to and to mitigate its effects (Barnes et al. 2013; Baul and McDonald 2015; Chanza and De Wit 2016; Reyes-García et al. 2016; Altieri and Nicholls 2017; Magni 2017; Khanal et al. 2018). Through time, Indigenous Peoples and Local Communities (IPLC) with a long history of interaction with the environment have dealt with and overcome many changes and extreme weather events, developing a knowledge system that allows them to adapt their daily activities to changing climatic conditions (Boillat & Berkes 2013; Hiwasaki et al. 2015; Turner & Spalding 2013). Indeed, since its recognition in the 1992 Convention on Biological Diversity (CBD) and the 2007 United Nation Declaration of the Rights of Indigenous Peoples, ILK has become a popular, even fashionable, topic in international spheres. For example, maintaining ILK has been one of the 2010 CBD Aichi targets; ILK has been included as a valid source of knowledge in the IPBES platform; and ILK has been considered important to achieve the Sustainable Development Goals (Buenavista et al. 2018; United Nations 2015). However, the transfer of intentions from the international spheres to the national, regional and local agendas is not so simple.

Actually, part of the climate change research community remains sceptical on the potential value of ILK. This part of the research community argues that many climate change impacts are difficult to detect without the adequate scientific instruments (Stone et al. 2013; Howe and Leiserowitz 2013; Cramer et al. 2014) and that the local nature of ILK hampers its extrapolation (Briggs 2013). Moreover, the epistemological differences between both knowledge systems, although for some are useful as they provide a greater understanding of the problem (Ford et al. 2016), for most are obstacles for the dialogue of both types of knowledge (Orlove et al. 2010; Adger et al. 2013). Finally, the different language used by scientists and IPLC to express their knowledge further prevents the equal participation of all the actors in the co-production of new knowledge (Conrad and Hilchey 2011).

Despite these critiques, other researchers have started to include ILK in climate change research. This has been done mainly in vulnerability assessments, adaptation frameworks, and action plans (Dazé et al. 2011; Pasteur 2011). However, although the inclusion of ILK in vulnerability and mitigation assessments somehow recognizes ILK ability to anticipate future negative impacts of climate change, ILK is not fully recognized as a potential data source for the collection of information on climate change impacts. Nonetheless, many authors have shown that IPLC are able to detect changes in local weather and climatic conditions and their subsequent impacts on the physical and biological systems on which their livelihoods depend (Fernández-Llamazares et al. 2015; Orlove et al. 2000; Weatherhead et al. 2010), see Reyes-Garcia et al. 2019 for a review). Moreover, numerous studies have shown the overlap between local and scientific information on a diversity of topics including temperature and rainfall trends (Klein et al. 2014; Baird et al. 2014; Da Silva et al. 2014; Oyerinde et al. 2015), fish stock declines (Brewer 2013; Gurgiser et al. 2016), or changes in vegetation index (Gamble et al. 2010), suggesting that information from both knowledge systems can be complementary. Particularly, insights from ILK would enrich the availability of data in now data-deficient regions (Belfer et al. 2017; Cai et al. 2017; Reyes-García et al. 2016; Sanchez et al. 2012; Savo et al. 2016; Wildcat 2013).

Furthermore, researchers increasingly argue that ILK could be used, in combination with scientific knowledge, in the co-production of new knowledge useful to orient more locally grounded adaptation and mitigation strategies (Huntington et al. 2004; Tengö et al. 2014; Ford et al. 2016; Berkes 2017) and to improve our understanding of climate change impacts (Savo et al. 2016; Reyes-García et al. 2019). Until recently, the comparison of information derived from different knowledge systems was used to validate ILK, so that this knowledge was acknowledged by the scientific community (Alexander et al. 2011; Panda 2016; Smith et al. 2017). However, IPLC and their advocates have argued that this process generates a situation of imbalance of power, in which the ILK has to be submitted and adapted to exogenous knowledge frameworks, often based on Western science (Berkes 2012; Cajete 2000; Johnson et al. 2016; Tengö et al. 2014). In response to this critique, many researchers advocate a respectful and inclusive knowledge integration that allows combining scientific knowledge and ILK (Agrawal 1995; Weber 2016; Berkes 2017; Turnhout et al. 2012; Watson & Huntington 2014). According to this view, each knowledge system should be evaluated and validated within their own reference frameworks (Tengö et al. 2014). This co-production of knowledge should be a collaborative process including ways to avoid power imbalances (Jasanoff 2004), a way back and forth that allows bridging a plurality of knowledge sources that are translated and assimilated by all parties and reach a common consensus of understanding and action (Armitage et al. 2011; Rathwell et al. 2015; Tengö et al. 2017). In a way, the creation of synergies for co-production of knowledge first requires that the scientific community, as a whole, recognizes the value of incorporating ILK into international agendas beyond climate change (Rigg and Mason 2018).

Within this framework, this work aims at gaining a better understanding of how scientists working on climate change value ILK. To do so, we first analysed the literature on local indicators of climate change impacts and then collected information through a web survey from 191 Spanish researchers working on climate change issues about the possibility of using information from ILK to identify climate change impacts. We analyse the match between scientists' responses and the presence of related local indicators of climate change impacts in the literature.

2. Methods

Our methodological approach compares results from a literature review documenting local observations of climate change impacts, with results from a web survey to Spanish scientists working on climate change issues.

2.1. Literature review

We reviewed articles collecting local observations of climate change impacts documented by IPLC. Following Reyes-García et al. 2016, for our search we used Scopus and Web of Science search engines and the following keywords: (i) indigenous knowledge, OR local knowledge, OR traditional knowledge, OR traditional ecological knowledge, AND (ii) observations, OR perceptions, OR indicators; AND (iii) climate change, OR global change, OR environmental change. We did not include any geographical limitations associated with our search. We obtained 273 articles from Scopus and 252 articles from Web of Science. We combined both lists and, after excluding duplicate articles, we kept 308 articles published until December 2016. Then, reading the articles in depth, we retained only 135 articles that included first-hand observations of climate change impacts documented among IPLC. Our criteria to determine whether a group could be considered as Indigenous Peoples was to follow the classification used by the authors of the article consulted. We excluded review and metadata articles (Savo et al. 2016), articles providing theoretical frameworks (Huntington et al. 2004), and articles reporting changes detected by scientific measurement devices (Ho et al. 2005). Articles were coded by a team of ten researchers following a common guideline. After each coder read and coded information from ten articles, the team discussed the coding system and solved potential discrepancies. Then the rest of the documents were analysed. The lead author conducted a final review to ensure accuracy in coding. As some papers documented impacts in different locations, from the 135 documents retained in our search, we have observations for 198 case studies.

For each document, coders noted all observations of climate change impacts reported in one location. Verbatim reports of observations of climate change impacts referring to the same phenomenon were grouped together (e.g., extreme rains and shorter but heavier rain). We call these aggregated observations local indicators of climate change impacts (LICCI) (Reyes-Garcia et al. 2016; Reyes-García et al. 2019).

Our LICCIs were classified in a hierarchical categorization of three levels. The upper level is defined by the main system in which the impact is detected. The climatic system represents changes related to atmospheric conditions and their repercussions on temperature, on the movement of air masses and on precipitation. The physical system includes changes related to the abiotic elements of the earth: hydrosphere (continental and oceanic water bodies), cryosphere and geosphere. The biological system encompasses the changes detected in wildlife, and the socioeconomic system represents the perceived impacts on agriculture, livestock, fisheries, forestry, human health and transport. The second level is formed by the sub-systems into which the four major systems are divided (e.g., the climatic system is divided into four sub-systems: temperature, rainfall, air masses and seasonal events). The third level includes LICCI groups within each sub-system (e.g., the subsystem temperature is divided into three groups: indicators related with mean temperature, indicators regarding extreme temperatures, and indicators of temperature fluctuation). Although all detected impacts depend directly or indirectly on changes in the climatic system, each observation was classified in the system and sub-system into which the change was perceived.

With this classification system, the 1357 observations documented were grouped into 75 different LICCI groups, re-grouped into 19 sub-systems, which were assigned to one of the main four systems (i.e., 4 of the sub-systems were assigned to the climatic system, 4 to the physical system, 5 to the biological system, and 6 to the socioeconomic system). This list of indicators was used to construct the web survey tool (see below). The classification of LICCI can be found in the Electronic Supplementary Material 1.

2.2. Sampling climate change scientists

We collected opinions on the potential contribution of ILK to climate research among Spanish scientists. We chose Spain as a case study for several reasons. First, we consider that the bridging between scientific knowledge and ILK should be done at the local level, for which we decide to work locally. Second, we focus on Spain because this country has a diverse geological relief that has favoured a large biological and ecological diversity that has favoured expertise diversity among climate change scientists. Moreover, the Iberian Peninsula, where Spain is found, is one of the areas of Europe where a greater increase in temperatures and drought is expected as a consequence of anthropogenic climate change (Füssel et al. 2017; Kendrovski et al. 2017). Finally, given our institutional affiliations and personal contacts, it was logistically easier for us to target this particular community of scientists.

To select scientists, we targeted university professors and members of research groups focusing on climate change issues, members of the Spanish Long-Term Ecological Research network (LTER), and researchers from the Spanish governmental research groups (CSIC) with a research line related to climate change. We also wrote personal e-mails to directors of National Parks belonging to the Spanish Global Change Monitoring Program requesting information on research groups that had performed climate change studies in their parks. Finally, we encouraged survey respondents to disseminate the survey among their contacts with related research topics.

Recruitment followed several stages. We sent an e-mail to scientists in our initial list (n=1077 contacts) explaining our goals and inviting them to voluntarily participate in our study. In the e-mail, we provided a link to the survey in Spanish and English. To encourage participation, we sent three reminders with 20 days of separation (Walston, Lissitz & Rudner 2006). As response rate was low, in a second round we reviewed the rest of the 87 recognized universities in Spain and included 1141 new contacts, for whom we followed the same procedure. In total we contacted 2218 scientists from 47 universities and 23 governmental research centers. We received 191 responses, 93 respondents from the first recruitment effort and 98 from the second, representing 8.61% of the initial sample. We received 137 answers in Spanish and 54 in the English version.

2.3. Web survey

We collected scientists' opinions on the potential contribution of ILK to climate research using a web survey, as this tool seems to efficiently capture the attention of the academic community (Kellner 2004). The survey was generated using the online application google forms and posted in a WordPress page created for this purpose (https://localindicatorsofclimatechange.wordpress.com/). The page was open to responses from February to August of 2018. The first part of the survey included respondent's sociodemographic information: gender, age, research centre, position (i.e., senior researcher, junior researcher, PhD student or technician), research topics of interest, and years of experience in the field of study.

In the second part of the survey, respondents were asked to report their opinion on the potential of including local knowledge[1] to detect indicators of climate change impacts. Overall, the survey included questions on 184 indicators identified in our literature review. We organized these

[1] In the survey we used the term Traditional Ecological Knowledge (TEK) instead of Indigenous and Local Knowledge (ILK) because ILK is a more recent expression defined by IPBES members (www.ipbes.net) and people from outside social-interdisciplinary fields are more familiarized with the term TEK. Here we have opted to use the more generic term *local knowledge*.

indicators into 68 groups, according with the subsystem they belonged, which in turn were regrouped into 17 independent modules corresponding to 17 subsystems. We excluded two sub-systems, human health and transport from our survey because the particular observations reported in the literature (i.e., increased hunger, physical injuries, insect-borne diseases or destruction of communication routes) did not seem relevant for the Spanish context. Respondents were instructed to answer only the modules for which they consider themselves as experts.

All modules were structurally identical but referred to different groups of LICCI. Thus, for each of the 68 groups of LICCI we first asked: 1) What is the need to collect more local level data on these indicators of climate change impacts? (without referring to local knowledge) and then 2) How feasible is to incorporate data from local knowledge on these indicators? For each of these questions, respondents had to give a score from 0 (i.e., no need to collect more local level data/ no possibility to incorporate data from local knowledge) to 10 (i.e., great need to collect more local level data / great possibility to incorporate data from local knowledge). The third question was composed by the list of indicators related to each group and documented in the literature review. In this question, we asked respondents to evaluate, according to their perception, the potential of local knowledge to contribute with data to these indicators. Responses to this question could also range from 0 (null contribution) to 10 (great contribution). The fourth and last question in each module requested informants to list other potential indicators derived from local knowledge that could contribute to increase our current knowledge of climate change impacts at local scale.

3. Data analysis

We first analysed results from the literature review on local indicators of climate change impacts. Particularly, we assessed the importance of the different groups of LICCI in previous literature by calculating the number of times each LICCI group appeared in the selected works and their relative frequency versus the total number of observations in our search.

We then analysed scientists' participation in our survey. To do so, we calculated participation in the different survey modules according to scientists' research area, gender, position, and years of experience in their field. After, we analysed scientists´ opinions on ILK relevance for climate change research by examining the four survey questions. Since informants' provided information on the contribution of various indicators belonging to the same group, which were often related, we created a variable that represents the average value of all indicators within a group. We called this variable aggregated indicator. To compare responses among systems and sub-systems, we performed Kruskal-Wallis nonparametric tests, because the sample did not meet the conditions of normality and homoscedasticity.

In our final analysis, we compared scientists´ opinions on the relevance of each indicator with the prevalence of the same indicator in the literature. Specifically, we compared the total number of LICCI documented on each sub-system with the average score obtained in the web survey on the same sub-system or module.

All statistical analyses were carried out with the SPSS program version 22 and the statistical applications of the Microsoft EXCEL program.

4. Results

4.1. Literature review

Among the 135 articles analyzed, we documented 1357 observations of climate change impacts. LICCI referring to the climatic system were mentioned in 88.89% of the articles (120 articles), LICCI referring to the physical system were mentioned in 78.52% (106 articles), LICCI referring to the biological system were mentioned in 45.93% (62 articles), and LICCI referring to impacts on the socioeconomic system were mentioned in 65.93% of the publications (89 articles). Moreover, almost half of the observations, 43.04% (584 obs.), referred to changes on the climatic system. Observations of impacts on the physical system represented 24.54% of all the observations collected, whereas only 10.83% of the observations referred to impacts on the biological systems (147 obs.). Finally, 21.59% (293 obs.) of the observations related to impacts on the socioeconomic system. A graph showing all the observations found in the literature review grouped by system and year of publication can be found in the Electronic supplementary material 3. Six of the 19 sub-systems in which we organized observations had more than 100 observations, of which three referred to the climatic system, two to the physical system, and one to the socioeconomic system (i.e., *agricultural system*). Rainfall was the sub-system with more observations (265 obs.), while the sub-systems with fewer observations was found within the biological system (Table 2.1, *Literature review* column).

4.2. Respondents' profile

Survey participants belong to 40 universities and 26 research centres in Spain. Scientists with more than 20 years of experience had a higher percentage of participation in the survey, accounting for 38.2% of all respondents (Table 2.2). Indeed, most survey respondents were senior researchers (70.2%) and 77.5% of participants had at least one decade of experience in their current field of research. Survey respondents varied in their research interests, which spanned across 43 different research lines. Most researchers (41.06%) focused on one of the branches of ecology, with only a few scientists (13.5%) coming from the socio-environmental perspective (see Electronic supplementary material 3). Overall, more participants considered themselves experts on the biological system (47.9%) (Table 2.2). More than half of the respondents (61.26%) answered only one module of the survey and 21.99 % two survey modules, representing 83.25% of the entire sample.

Table 2.1. Comparison of information on groups of local indicators of climate change impacts (LICCI): results from literature review compared with Spanish scientists' opinions. Comparison of (1) number and frequency of observations reporting LICCI found in the literature review. Average score out of 10 points on the web survey to questions on (2) the need to collect more local level data from indicators of climate change impacts, (3) the feasibility of incorporating data from local knowledge on climate change indicators and (4) the potential of indigenous and local knowledge (ILK) indicators found in the literature review, clustered in the variable aggregated indicator

			Literature review		Web Survey			
System	Sub-system	Group of LICCI	Reports in the literature		Scientists answered the module	Need to collect local level data	Feasibility to incorporate local knowledge data	Potential of ILK indicators found in the literature aggregated indicator
			n	%	n	Avg. score	Avg. score	Avg. score
Climatic system	Temperature	Mean temperature	93	6.85	32	7.72	6.88	5.91[2]
		Extreme temperature	33	2.43	32	8.25	7.19	6.37[4]
		Temperature fluctuations	6	0.44	32	7.72	6.72	6.50[2]
		Total / (average score)	*132*	*9.73*	32	(7.90)	(6.93)	(6.26)
	Rainfalls	Clouds and fog	12	0.88	18	8.28	6.33	5.61[5]
		Mean rainfalls	90	6.63	19	**8.74**	7.32	6.84[3]
		Extreme rainfalls	29	2.14	19	**9.32**	7.37	7.17[4]
		Rainfall fluctuation/ unpredictable precipitation	90	6.63	19	**9.16**	6.84	7.02[3]
		Drought	44	3.24	19	**9.37**	8.21	7.68[2]
		Total / (average score)	*265*	*19.53*	19	**(8.97)**	(7.21)	(6.87)
	Air masses	Wind	40	2.95	5	**9.40**	6.20	5.90[4]
		Storm (hail storm/dust storm/-sandstorm)	28	2.06	5	**9.40**	6.60	6.25[4]
		Cyclones and tornadoes	10	0.74	5	**9.40**	6.80	6.65[4]
		Total / (average score)	*78*	*5.75*	5	**(9.40)**	(6.53)	(6.27)
	Seasonal events	Shifts in seasonal patterns	44	3.24	26	**9.08**	7.08	6.90[2]
		Duration and timing of seasons	65	4.79	26	**8.96**	7.15	6.75[3]
		Total / (average score)	*109*	*8.03*	26	**(9.02)**	(7.12)	(6.83)
Physical system	Ocean/sea	Sea temperature	3	0.22	15	7.73	4.93	4.73[1]
		Sea-level rise	17	1.25	15	7.67	6.27	5.71[3]
		Coastal erosion/sedimentation	9	0.66	14	8.21	6.85	6.32[2]

Table 2.1 (continued)

			Literature review		Web Survey			
		Ocean currents	3	0.22	14	8	6.36	5.46[2]
		Ocean salinity	1	0.07	14	6.79	4.21	3.79[1]
		Total / (average score)	*33*	*2.43*	15	(7.68)	(5.73)	(5.20)
	Continental waters	Mean river flow	36	2.65	28	**8.82**	7.71	7.61[2]
		Change in river floods	30	2.21	28	8.46	7.86	7.29[3]
		Water temperature of rivers and Lakes	2	0.15	29	**8.76**	6.07	5.45[1]
		Lake level	10	0.74	27	**8.67**	7.78	7.28[2]
		Fresh water availability/quality	52	3.83	28	**8.64**	7.79	7.31[4]
		Phreatic/underground water	11	0.81	27	**9.19**	7.74	7.58[3]
		River-bank erosion / sedimentation	8	0.59	28	**8.61**	6.43	5.68[3]
		Total / (average score)	*149*	*10.98*	29	**(8.74)**	(7.34)	(6.88)
	Soil	Soil erosion/landslides	27	1.99	19	**8.84**	7.58	6.26[2]
		Soil moisture	14	1.03	18	**8.72**	6.89	6.19[3]
		Soil temperature	2	0.15	18	7.67	5.50	5.03[2]
		Earthquake and tsunamis	1	0.07	12	7.25	6.08	5.29[2]
		Total / (average score)	*44*	*3.24*	19	(8.12)	(6.51)	(5.69)
	Ice/snow	Snow cover	41	3.02	5	**9.00**	7.40	6.87[3]
		Ice sheet/lake and river ice	21	1.55	5	**8.80**	7.20	6.93[3]
		Glaciers	20	1.47	5	**9.40**	7.00	7.20[2]
		Permafrost	10	0.74	4	7.75	5.25	6.25[1]
		Ice-sea	15	1.11	–	–	–	.
		Total / (average score)	*107*	*7.89*	5	**(8.74)**	(6.71)	(6.81)
Biological system	Marine non-fish species (spp)	Marine non-fish spp.'s abundance	10	0.74	13	**9.00**	7.77	6.74[3]
		Marine non-fish spp.'s invasive alien species (IAS)	0	0.00	13	**9.00**	**8.62**	7.23[1]
		Marine non-fish spp.'s diseases/pest and	14	1.03	13	**8.54**	7.00	6.13[3]
		Marine non-fish spp.'s phenology / distribution and reproduction	3	0.22	13	**8.92**	7.62	6.49[3]

Table 2.1 (continued)

		Literature review		Web survey			
	Total / (average score)	*27*	*1.99*	13	**(8.87)**	(7.75)	(6.65)
Wild flora	Wild plants and fungi's abundance	14	1.03	45	**8.80**	7.29	7.07[2]
	Wild plants and fungi's IAS	3	0.22	43	**8.98**	7.42	7.12[2]
	Wild plants/fungi's disease-pest and mortality	2	0.15	40	**8.93**	7.75	7.74[1]
	Wild plant and fungi's phenology/distribution and reproduction	20	1.47	44	**9.00**	7.93	7.48[5]
	Natural habitat degradation and disappearance	11	0.81	–	**–**	–	–
	Total / (average score)	*50*	*3.68*	45	**(8.93)**	(7.60)	(7.35)
Terrestrial vertebrates	Terrestrial vertebrates' abundance	17	1.25	20	**8.95**	7.85	7.21[4]
	Terrestrial vertebrates' IAS	5	0.37	19	**9.21**	8.42	7.58[1]
	Terrestrial vertebrates' disease-pest and mortality	13	0.96	19	**8.74**	6.79	5.70[3]
	Terrestrial vertebrates' phenology/distribution and reproduction	13	0.96	19	**9.37**	8.00	6.75[5]
	Total / (average score)	*48*	*3.54*	20	**(9.07)**	(7.77)	(6.81)
Birds	Birds' abundance	7	0.52	15	**8.87**	7.80	7.60[4]
	Birds' IAS	0	0.00	14	**9.00**	7.57	7.79[1]
	Birds' disease-pest and mortality	1	0.07	14	8.21	6.36	5.75[2]
	Birds' phenology/distribution and reproduction	8	0.59	15	**9.13**	8.27	7.51[3]
	Total / (average score)	*16*	*1.18*	15	**(8.80)**	(7.50)	(7.16)
Arthropods	Arthropods' abundance	2	0.15	13	**8.77**	7.15	7.28[3]

Table 2.1 (continued)

			Literature review		Web Survey			
		Arthropods' IAS	1	0.07	13	**8.69**	7.54	7.80[2]
		Arthropods' disease-pest and mortality	0	0.00	13	**8.54**	7.23	7.77[1]
		Arthropods' phenology/distribution and reproduction	3	0.22	13	**9.08**	7.38	6.82[6]
		Total / (average score)	*6*	*0.44*	13	**(8.77)**	(7.33)	(7.42)
Socioeconomic system	Agriculture	Crop's productivity	42	3.10	28	8.32	8.43	7.58[3]
		Crop's disease-pests and weeds	39	2.87	29	**8.55**	**8.52**	7.85[4]
		Crop's phenology and growing patterns	14	1.03	26	**9.08**	**8.69**	8.18[4]
		Soil degradation and fertility	15	1.11	26	**8.54**	7.65	6.31[2]
		Total / (average score)	*110*	*8.11*	29	**(8.62)**	(8.32)	(7.48)
	Forestry	Forest cover	23	1.69	25	8.48	7.56	7.17[5]
		Forest fires	7	0.52	25	8.12	7.80	7.04[1]
		No timber forest products availability/quality	15	1.11	25	**8.64**	8.04	7.36[3]
		Total / (average score)	*45*	*3.32*	25	(8.41)	(7.80)	(7.19)
	Livestock and pastures	Livestock productivity and quality	7	0.52	7	**9.57**	**9.14**	7.57[2]
		Livestock's disease	20	1.47	7	**8.86**	8.43	7.43[3]
		Livestock's phenology and reproduction	1	0.07	7	**8.71**	8.00	7.64[2]
		Pasture's availability and quality	20	1.47	7	**9.43**	**9.14**	8.14[2]
		Total / (average score)	*48*	*3.54*	7	**(9.14)**	**(8.68)**	(7.70)
	Fisheries	Fish stock's abundance	20	1.47	9	**8.78**	8.44	7.28[4]
		Fish's IAS	4	0.29	9	**8.78**	**9.11**	8.00[1]
		Fish's disease - mortality – pest and parasites	4	0.29	9	7.89	7.00	7.00[3]
		Fish's phenology/distribution and reproduction	12	0.88	9	**8.67**	**8.78**	7.67[3]

Table 2.1 (continued)

		Literature review		Web survey			
	Total / (average score)	*40*	*2.95*	9	**(8.53)**	(8.33)	(7.49)
Human health	Diseases	19	1.40	–	–	–	–
	Health injuries, physical affection	9	0.66	–	–	–	–
	Hunger	11	0.81	–	–	–	–
	Cultural/spiritual and identity values	8	0.59	–	–	–	–
	Total / (average score)	*47*	*3.4*	–	–	–	–
Transport	Trails	3	0.22	–	–	–	–
	Total / (average score)	*3*	*0.22*	–	–	–	–

*Boldface values represent values ≥8.5

[a] Values in parentheses represent the average score of the LICCI groups of each sub-system

[b] Superscripts denote the number of indicators that were asked for each group of LICCI

[c] Italic values represent the total number and frequency of observations of each subsystem found in the literature review

Table 2.2. Description of web survey respondents

Variable	Group	n	%	Average age	Average years of experience
Gender	Male	123	64.40	47.29	20.05
	Female	68	35.60	41.26	14.65
Years of experience	0–4 years	23	12.04	28.23	2.87
	5–10 years	38	19.90	37.02	8.39
	11–20 years	57	29.84	44.32	16.67
	> 20 years	73	38.22	55.5	29.14
Position	Senior researcher	134	70.16	50.08	22.68
	Junior researcher	24	12.57	35.54	9
	PhD student	22	11.52	28.77	3.72
	Technician	11	5.76	41.9	11.27
Reported expertise	Climatic system	54	28.27	46.47	18.53
	Physical system	60	31.41	46.30	18.67
	Biological system	91	47.64	46.85	20.05
	Socioeconomic system	55	28.8	42	14.21
Number of systems answered in the survey	1 system	136	71.02	45.15	18.49
	2 systems	44	23.04	43.76	15.98
	3 systems	8	4.19	48.5	22
	4 systems	3	1.57	57.33	22.67
Number of sub-systems answered in the survey	1 sub-system	117	61.26	45.54	18.90
	2 sub-systems	42	21.99	42.08	15.05
	3 sub-systems	14	7.33	44.64	16.64
	4 sub-systems	12	6.28	47.42	20.04
	5 sub-systems	3	1.57	49.67	18.33
	6 sub-systems	3	1.57	60.67	30

4.3. Spanish scientists´ opinions regarding the potential contribution of local knowledge to climate change research

A different number of participants answered each of the 17 survey modules. The module of wild flora was the most popular, being answered by 45 participants, followed by the modules of temperature (n=32), continental waters (n=29), and agriculture (n=29) (Table 2.1). On the other extreme, the modules on air masses and ice-snow were the modules answered by fewest participants, five each.

Responses to the question on the need to continue collecting local level data varied from one system to another. Thus, scores to the question on the need to collect local level data were higher for modules on the biological than on the other systems (χ^2= 12.92; p-value= 0.005). Additionally, respondents also considered that the incorporation of local knowledge into climate change studies was less feasible when referring to indicators on the climatic and the physical systems than when referring to indicators on the biological and the socioeconomic systems. Along the same line, results from the analysis of the variable aggregated indicator also showed statistically significant differences in scientists' opinion on the potential of local knowledge to contribute through specific indicators, with scientists reporting that local knowledge could be particularly relevant to measure climate change impacts on the socioeconomic system (χ^2= 30.78; p-value= 0.000).

Scientists generally agreed on the need to collect more local level data for most of the groups of indicators, although there were some statistically significant differences between groups (χ^2= 96.66; p-value= 0.010). Overall, respondents considered that the need to collect additional local level data was highest for the module air masses (average score 9.40 out of 10, where 10 indicates the maximum need to collect local data, Table 2.1). In contrast, scientists considered that the need to collect additional local level data on indicators of ocean salinity was lowest (average score of 6.79 out of 10). Scientists gave high scores to the question on the need to collect additional local level data to all groups of indicators in the biological system, as well as to several groups of indicators in the socioeconomic system, and particularly to the availability of pasture and livestock productivity or phenological changes on crops. Overall, 50 of the 68 groups of indicators (73.53%) got an average score ≥ 8.5 out of 10 on the need to collect more local level data.

Results to the question on the feasibility of incorporating data from local knowledge into current indicators of climate change impacts vary across systems. The average of scientists' scores regarding the possibility of incorporating local knowledge data into climate change research was higher than 8.5 (out of 10) for only seven groups (10.29%; Table 2.1), with statistically significant differences between groups (χ^2= 148.26; p-value= 0.000). Thus, participants saw more opportunities for the inclusion of local knowledge data into for groups of indicators of climate change impacts in the biological and socioeconomic systems than in the climatic and physical systems. Six of the 15 groups in the socioeconomic system had an average score over 8.5 points. The variable aggregated indicator, merging specific indicators collected from the literature also showed statistically significant differences among groups of indicators (χ^2= 150.66; p-value= 0.000). Aggregated indicator related with fisheries, livestock and pasture, and agriculture obtained the highest scores.

4.4. LICCI reported in the literature versus Spanish scientists' perceptions

In our final analysis, we compare results from the literature review with scientists' responses to our survey (Fig. 2.1). Overall, we find an important mismatch between LICCI documented in the literature and scientists' opinion on local knowledge potential to contribute to climate change research. According to results from our literature review, most studies documenting LICCI have reported impacts on the climatic and the physical systems (n= 917 obs.; 67.58%). Moreover, apart from impacts on the agricultural sub-system (n=110 obs.), the literature reports relatively few impacts on the biological and socioeconomic systems. Conversely, although researchers argue that it is important to collect more local level data for all the systems, results suggest that researchers consider that such data collection is more relevant for impacts on the biological system (χ^2= 12.92; p-value= 0.005). Interestingly, researchers also considered that incorporating local knowledge on climate change research had a higher potential when data referred to the biological and socioeconomic systems than to the climatic and physical systems (χ^2= 56.61; p-value= 0.000). Specifically, surveyed scientists considered that local information could best help to detect climate change impacts on agriculture, livestock and pastures, and fisheries, questions that had an average score of 8.3, 8.7 and 8.3 points out of 10 respectively (Table 2.1).

Finally, we examined the list of LICCI proposed by respondents in response to the last question, on other possible indicators to be included. We documented 157 comments, of which only 64 were new indicators. The remaining comments included indicators already proposed in other modules, indicators that require the use of scientific measurement devices, and other type of comments. The most abundant new indicators proposed related to agriculture, followed by indicators on continental waters, with a clear predominance of indicators related to the socioeconomic system. This list can be found in the Electronic Supplementary material 4.

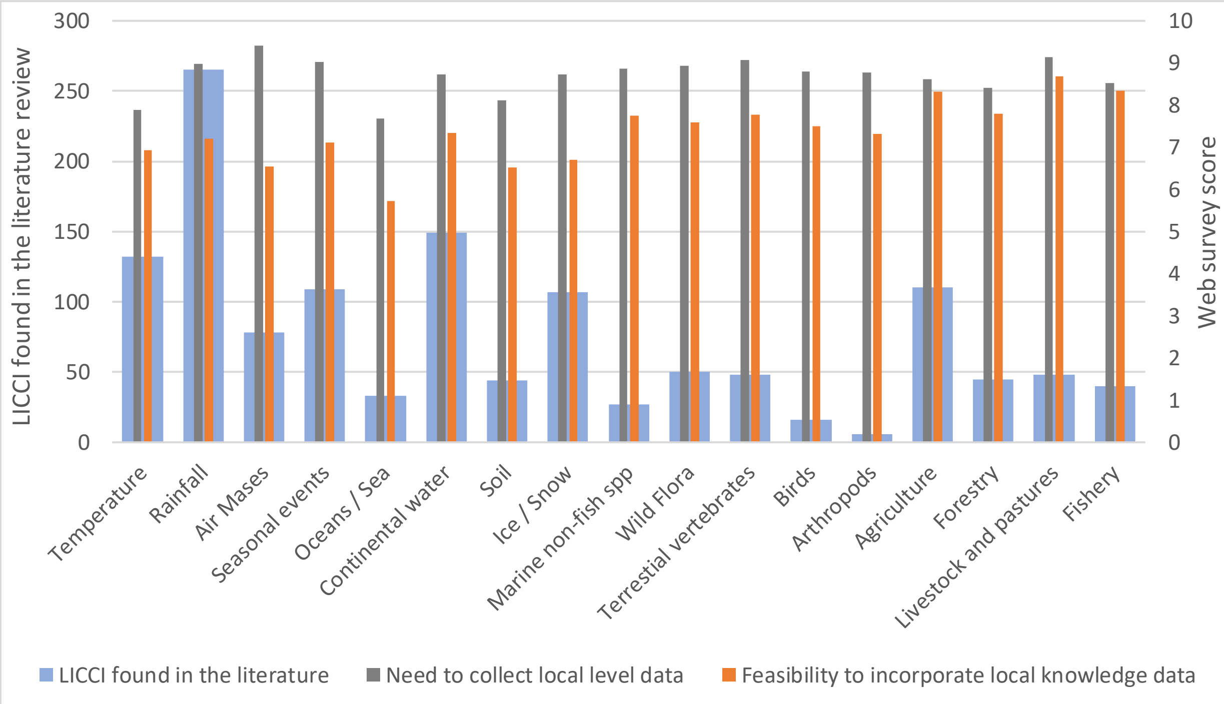

Figure. 2.1 Number of observations reporting Local Indicators of Climate Change Impacts (LICCI) found in the literature review compared with scientists' opinion collected through a web survey about (1) the need to collect more local level data and (2) the feasibility to incorporate data from local knowledge into the different sub- systems

5. Discussion

This work assesses Spanish scientists' opinion on the importance and feasibility of including local knowledge on climate change impacts research. Before we discuss the main findings of this work, we point at some methodological limitations that should be considered when interpreting our results.

The main limitations of our work relate to sampling and survey design. First, while our literature review included works from around the world, our survey sample was limited to Spanish scientists. Although Spanish scientists work in many geographical areas of the world, we did not collect information on scientists' geographical focus, for which we cannot test for potential geographical biases in answers. Moreover, as participation was voluntary, our sample might suffer from self-selection bias, for example related to disciplines or geographical areas, for which we do not know whether the sample is representative of the entire Spanish scientific community. Considering those potential biases and the fact that ours is the first survey of this kind, the extrapolation of our results beyond our sample should be made with caution. Second, issues related to survey design and the classification of indicators proposed should also be taken into account in the interpretation of results. Thus, although we instructed respondents to focus on indicators related to their field of expertise, we cannot check whether this instruction was followed. Moreover, our survey included questions on indicators from the literature whose temporal validity was not checked, whereas the survey focused on contemporary information. Finally, some of the survey questions were too vague and general, while the incorporation of local knowledge is often context-dependant. These issues related to the design of our survey call for caution when interpreting results but are also important to notice for future work on this line.

Keeping these limitations in mind, we now discuss the four main findings of this work. The first finding of this work relates to results from the literature review showing that researchers documenting LICCI have mainly focused on changes in rainfall, continental waters, and temperature, although there are also many observations of change on ice-snow, seasonal events, and agriculture. Indeed, these six sub-systems represent 64,21% of all observations documented. The prevalence of reports related to the climatic system might relate to the fact that climate change affects firstly this system, with cascading impacts on other systems (Johnson et al. 2011; Xu et al. 2009). However, the finding might also reflect pressures of the scientific community to validate ILK comparing local perceptions with scientific knowledge (Johnson et al. 2016). As the scientific community has longer and more complete time series of changes on the climatic and physical systems than on the biological system, researchers working on local observations of climate change impacts might find it difficult to compare their results with data from the biological system, which still has many information gaps (McRae et al. 2017).

The second important finding from this work is that Spanish scientists working on climate change generally agree on the need to continue collecting more local level data to monitor climate change impacts, particularly on the biological system. While climatic models have improved through the exponential increase of weather stations (Pierce et al. 2009; Rummukainen 2010), they do not yet allow one to predict climate change impacts on the local biological systems. Earth system models are increasingly including interactions between the climatic and biophysical systems like the carbon cycle, terrestrial and marine biochemistry and ecosystems and natural and human impacts (Bonan and Doney 2018), but they continue to be imprecise (Pearson and Dawson 2003; Getz et al. 2018). Lack of or deficient information on species presence, species vulnerability, species geographical distribution, or interspecies relation makes difficult the transferability of models (McMahon et al. 2011; Pimm et al. 2014; Yates et al. 2018). Such paucity of data on biological systems might be one of the reasons why researchers insisted on the need to continue collecting local level data from the biological systems to monitor climate change impacts.

Related to this, the third finding of this work is that some modules of the socioeconomic system (livestock and pastures´ productivity and quality, fish´s invasive alien species or crop´s phenology and growing patterns) were the ones that, according to Spanish scientists, offered highest potential to incorporate data from local knowledge detecting climate change impacts. Additionally, survey respondents saw a large potential for local observations to contribute to detect impacts on a few modules of the biological system, particularly on terrestrial vertebrates' diseases, marine invasive alien species, or bird phenological and reproduction patterns. Interestingly, these results are in line with the current increase in citizen science projects. A potential explanation for the fact that participants saw more opportunities for the inclusion of local knowledge into climate change research for LICCI groups in the biological and socioeconomic system is the fact that many participants had expertise in those topics. However, a large part of the scientific community recognizes that lay citizens can be a great help to increase the number of records of animal and plant species that can contribute to improve our knowledge about the state of conservation, distribution and evolution of species (Silvertown 2009; Dickinson et al. 2012), and some countries have already taken the initiative in this task, including the voice and perspective of indigenous communities in climate change research, such as New Zealand or the Artic councils (ACIA 2005). Results from our survey suggest that more work on this line would be useful.

It is worth mentioning that Spanish scientists found scarce potential to incorporate data from local observations of impacts on the climatic and the physical systems, and particularly on the air masses, ocean and seas and soil. While these results may be due to the different number of participants who answered the different modules of the survey, they might also reflect the view of experts on this particular field. Indeed, as mentioned above, some climate researchers have argued that local knowledge has difficulties to contribute to climate research because this type of knowledge cannot accurately perceive changes without using scientific devices (Howe & Leiserowitz 2013). The groups of indicators considered less suitable to incorporate local knowledge are, precisely, the ones for which scientists typically rely on measuring devices such as weather stations or CTD (conductivity, temperature, and depth) to measure marine salinity. Overall, this finding suggests that, while there is a large agreement on the need to collect more local level data, sectors of the scientific community still have issues on the feasibility to incorporate inputs from local knowledge into climate change research.

The last finding of this work relates to the mismatch between the most frequent indicators of climate change impacts found in the literature review and the indicators considered by researchers as the most suitable to incorporate inputs from local knowledge into climate change studies. While the LICCI most often documented in the literature relate to rainfall, temperatures, or continental waters, Spanish climate change scientists identified LICCI related to agriculture, livestock and pastures and fisheries as the ones with highest potential to contribute to climate change studies. Indeed, local knowledge on those topics could reduce the difficulties of attribution of drivers of change that climate change scientists face when analysing impacts in the biological and socioeconomic systems (Cramer et al. 2014). The continuous modifications of human-managed systems generate a lack of long-time series on stable managed systems. However, IPLC that have preserved traditional agricultural, shepherd, hunting or fishing practices for centuries could help scientists discern the unprecedented impacts generated by climate change without the influence of other drivers.

6. Conclusion

During several decades, a growing number of works, sometimes in partnership with IPLC, have examined ILK contributions to climate change research. Most of this work points at the overlap of ILK and scientific data. Moreover, recent work suggests that combining knowledge from different knowledge systems is not only possible but also desirable, as it can contribute to improve our understanding of pressing issues, like climate change (Tengö et al. 2014). In this sense, results from this work suggest that for local knowledge to contribute to climate change research, researchers need to leave behind the need to demonstrate the overlap of scientific data and local observations of impacts on the climatic system, and focus on impacts on the biological and socioeconomic systems, which can contribute better to increase our current knowledge on climate change effects. In other words, researchers should seek collaboration with IPLC to co-produce knowledge that helps us to better understand how climate change is particularly affecting them. For this purpose, it is necessary to create an interdisciplinary collaboration network at different scales, which includes IPLC, climate change researchers, researchers working with IPLC and the administrations of those specific geographic regions to achieve a real inclusion of ILK into climate change studies.

Compliance with ethical standards

This research received the approval of the Ethics committee of the Autonomous University of Barcelona (CEEAH 3581 and CEEAH 4781).

7. References

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Journal: Climatic change

Including Indigenous and local knowledge in climate research. An assessment of the opinion of Spanish climate change researchers.

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Electronic supplementary material 1.

Table 2.3. Proposed classification of Local Indicators of Climate Change Impacts (LICCI) found in the literature review.

Group of LICCI	List of LICCI that define each group
Mean temperature	Increase-decrease mean temperature More-fewer number of warm days More- fewer number of cold days More- fewer number of sunny days Increase-decrease sunshine intensity Increase-decrease daytime/ night time temperature Increase- decrease temperature related with altitude Increase-decrease wind temperature
Extreme temperature	More- fewer heat-cold waves Increase-decrease frost intensity Increase-decrease extreme temperature Increase-decrease intensity of cold-heat waves Increase-decrease length of cold-heat waves More- fewer number of frost days Increase-decrease extreme cold-hot wind episodes
Temperature fluctuations	Increase-decrease unusual temperature shifts Increase-decrease unusual cold-heat waves
Mean rainfalls	Increase-decrease mean rainfall Increase-decrease annual rainfall variation More-fewer number of rainy days More-fewer dry days
Extreme rainfalls	Increase-decrease intensity of heavy rainfall Increase-decrease frequency of heavy rainfall Increase-decrease flash rainfall flood Increase-decrease shorter but heavier rain Increase-decrease intense rainfall events Increase-decrease natural disasters related with rainfall
Rainfall fluctuation/ unpredictable precipitations	More-fewer patchy rains Increase-decrease occurrence of dry spells More-fewer unpredictable rainfall Increase-decrease lack of rain during certain periods Increase-decrease rainfall variability Change in timing of rainfall More-fewer irregular or erratic rainfall Increase-decrease poor and unreliable rainfall Change precipitation patterns Increase-decrease extended rainfall More-fewer delayed rainfall People cannot predict rains anymore More-fewer rainfall fluctuations Increase-decrease uneven distribution of rainfall
Drought	Increase-decrease frequency of drought More-fewer absence-total lack of rainfall Increase-decrease frequency of dry seasons

	Earlier-later drought More-fewer dry years
Clouds and fog	Increase-decrease cloud size Increase-decrease cloud thickness More-fewer clouds More-fewer fog-mist or cloudy days Increase-decrease duration of fog Change colour of clouds
Wind	Increase-decrease strong winds More-fewer windy days Changes in wind direction Increase-decrease wind speed
Storm (hail /dust /sand)	Increase-decrease frequency of storms Increase-decrease intensity of storms-hail storms-dust storms Increase-decrease of lightning and thunder
Cyclones, tornadoes	Increase-decrease frequency of cyclones-tornadoes More-fewer number of cyclones-tornadoes More-fewer heavy storms never seen before, becoming tornadoes
Shifts in seasonal patterns	More-fewer extreme seasons Shifting in seasonal patterns More-fewer rapid seasonal transitions Increase-decrease unusual seasonal patterns e.g. snow in summer
Duration and timing of seasons	Increase-decrease length of seasons Increase-decrease length of seasonal events (monsoon) Shifts in beginning- end of seasonal events (early or late beginnings and ends e.g. monsoon, ice, sea- ice)
Sea temperature	Increase-decrease sea surface temperature Increase-decrease water temperature of each seasons
Sea-level rise	Increase-decrease sea level Increase-decrease size of waves Increase-decrease coastal flooding More-fewer islands disappearing
Coastal erosion / sedimentation	Increase-decrease surface of beach Increase-decrease coastal surface Change structure of beach soil: more-less sand-rocks Increase-decrease shoreline erosion Increase-decrease depth of bays
Ocean Currents	Increase-decrease ocean currents speed-strength Changes in currents direction
Ocean Salinity	Increase-decrease ocean salinity
Mean river flow	Increase-decrease river water flow Increase-decrease river depth Increase-decrease frequency of dying rivers More-fewer river paths disconnected
Change in river floods	Increase-decrease river-flood extension Increase-decrease river-floods frequency Increase-decrease river-flood intensity
Fresh water availability / quality	Increase-decrease water quality Increase-decrease water availability Increase-decrease water pollution More-fewer dissolved particles in water Change in snow and water taste More-fewer number of wells More-fewer ponds have dried up Increase-decrease house water Increase-decrease surface water
Water temperature of rivers and lakes	Increase-decrease water temperature of rivers-lakes
Lake level	Increase-decrease lake water level

	Increase-decrease duration of temporal lakes More-fewer lakes are disappearing
Phreatic / Underground water	Increase-decrease phreatic level Increase-decrease aquifer recharge Change groundwater level during the year Increase-decrease depth of water Increase-decrease wetland surface
River bank erosion / sedimentation	Increase-decrease river erosion-sedimentation Change places of sedimentation deposit Increase-decrease river sedimentation Increase-decrease river erosion intensity
Soil erosion / landslides	Increase-decrease soil erosion Increase-decrease soil sedimentation Increase-decrease landslides More-fewer rocky soil Increase-decrease soil desertification Increase-decrease loss of soil
Soil moisture	Increase-decrease soil humidity/dryness Increase-decrease evaporation from the soil Increase-decrease water infiltration More-less water in soils
Soil temperature	Increase-decrease soil temperature
Earthquake and tsunamis	Increase-decrease intensity- Increase-decrease frequency of earthquakes and tsunamis
Snow cover	Increase-decrease amount of snow Increase-decrease erratic or irregular snow patterns More-fewer snowfalls Increase-decrease snowfall frequency Increase-decrease snow depth Increase-decrease crusty snow patches Increase-decrease snow duration More-less permanent snow
Ice sheet / Lake and rive ice	Changes in ice properties Increase-decrease ice thickness Complete-incomplete freeze of river/lakes Increase-decrease melting patterns
Glaciers	Increase-decrease glacier size Glacier shrinkage or receding (excluding permafrost and sea ice) Increase-decrease movement of glaciers
Permafrost	Increase-decrease permafrost surface Increase-decrease discontinuous permafrost Increase-decrease depth variation Increase-decrease thawing-melting of permafrost
Sea- Ice	Increase-decrease sea-ice surface Increase-decrease sea-ice thickness
Marine non-fish species (spp) abundance	Increase-decrease abundance of marine non-fish spp (mammals, coral, sponges, cnidarians, algae, sea grass…) Increase-decrease disappearance of marine non-fish spp New marine non-fish spp
Marine non-fish spp Invasive Alien Species (IAS)	More-fewer spp stated as invasive
Marine non-fish spp Diseases / pest / mortality	Increase-decrease marine non-fish spp disease - parasites Increase-decrease coral bleaching More-fewer marine non-fish spp malformations
Marine non-fish spp Phenology / Distribution & reproduction	Changes in marine non-fish spp migration time Changes in marine non-fish spp mating time Changes in marine non-fish spp breeding time Changes in marine non-fish spp distribution

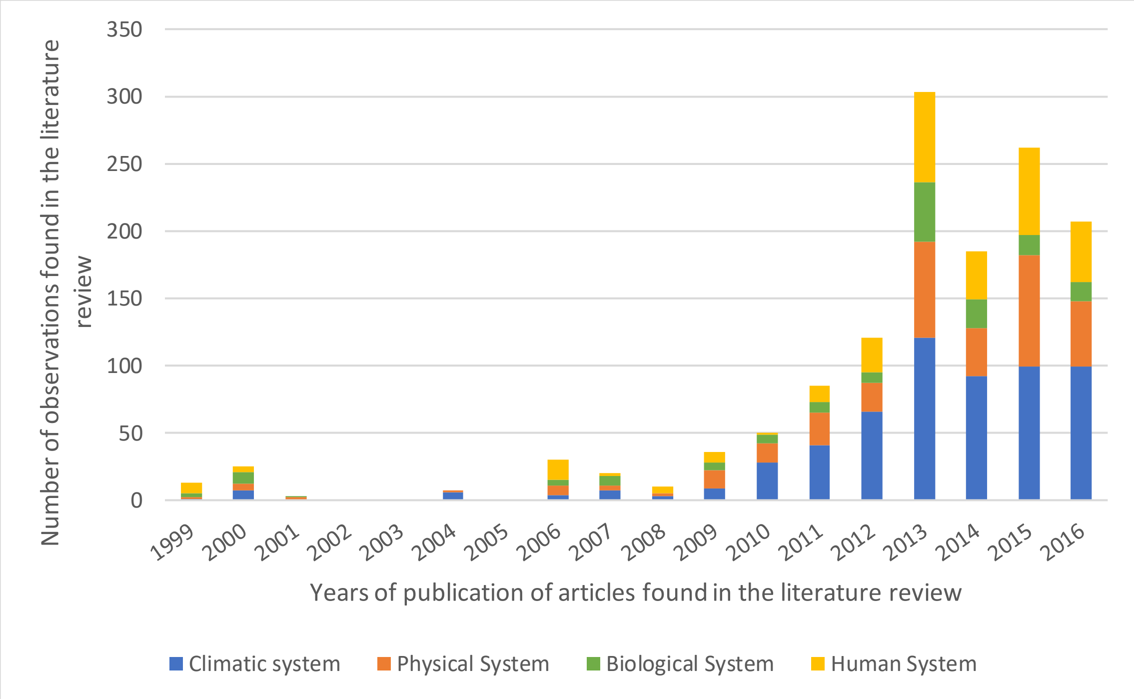
Wild plants and fungi abundance	Increase-decrease abundance of plants Increase-decrease vegetation density Increase-decrease disappearance of plants Change vegetation type
Wild plants & fungi IAS	More-fewer spp stated as invasive
Wild plants & fungi Disease-pest-mortality	Increase-decrease plant mortality Increase-decrease plant diseases/pests
Wild plant & fungi Phenology / Distribution & reproduction	Changes in plant phenology Change in flowering time- blooming time-fruiting time Increase-decrease perennial trees not flowering Increase-decrease vegetation heights Increase-decrease tree height Increase-decrease plants growing speed Change in flora distribution
Natural habitat degradation & disappearance	Increase-decrease habitat degradation Increase-decrease landscape change Increase-decrease biodiversity loss Increase-decrease landscape disappearance Increase-decrease ecosystem productivity (excluding agricultural) Increase-decrease loss of specific landscape elements Increase-decrease habitat fragmentation
Terrestrial vertebrates abundance	Increase-decrease abundance of terrestrial vertebrates (mammals-amphibians-reptiles) More-fewer migratory spp Increase- decrease terrestrial populations Increase-decrease disappearance of terrestrial vertebrates New terrestrial vertebrates
Terrestrial vertebrates IAS	More-fewer spp stated as invasive
Terrestrial vertebrates Disease- starving-pest-mortality	Increase-decrease terrestrial vertebrate diseases Increase-decrease appearance of terrestrial vertebrate pests Increase-decrease vector-borne disease (flies-mosquitoes- ticks) More-fewer terrestrial vertebrate malformations Increase-decrease size of terrestrial vertebrates More-fewer hungry or skinny terrestrial vertebrates Increase-decrease mortality of terrestrial vertebrates
Terrestrial vertebrates Phenology / Distribution & reproduction	Increase-decrease unusual animal behaviour Change in terrestrial vertebrates´ hibernation time Change in terrestrial vertebrates´ migration time Change in terrestrial vertebrates´ mating time Change in terrestrial vertebrates´ breeding time Change in terrestrial vertebrates' distribution Change in terrestrial vertebrates´ migration areas Increase-decrease reproduction effectivity in terrestrial vertebrates More-fewer number of egg-pups-offspring of terrestrial vertebrates
Bird abundance	Increase-decrease abundance of birds Increase-decrease bird populations More-fewer migratory spp More-fewer bird spp disappeared New bird spp
Birds IAS	More-fewer spp stated as invasive
Birds Disease-pest-mortality	Increase-decrease bird diseases More-fewer bird malformations Increase-decrease size of birds More-fewer hungry or skinny birds Increase-decrease mortality of birds
Birds Phenology / Distribution & reproduction	Increase-decrease unusual bird behaviour Change in birds´ hibernation time Changes in birds´ migration time Changes in birds´ mating time

	Changes in birds´ breeding time Change birds´ distribution Change birds´ migration areas Increase-decrease reproduction effectivity in birds More-fewer number of eggs of birds
Arthropods abundance	Increase-decrease abundance of arthropods Increase-decrease arthropod populations Disappearance of arthropod spp New arthropods spp
Arthropods IAS	More-fewer spp stated as invasive (different from crop pests) e.g. Asian wasp
Arthropods Disease-pest-mortality	Increase-decrease arthropod disease (e.g. *varroa*) Increase-decrease mortality of arthropods
Arthropods Phenology / Distribution & reproduction	Increase-decrease unusual arthropod behaviour Change in arthropods´ hibernation time Change in arthropods´ migration time Change in arthropods´ mating time Change in arthropods´ distribution Change in arthropods´ migration areas Increase-decrease reproduction effectivity in arthropods More-fewer number of eggs of arthropods
Crop productivity	Increase-decrease agricultural-crops productivity Increase-decrease size of fruits More-fewer successful/failed annual crop Change of growing patterns
Crop disease. Pests & weeds	Increase-decrease crop diseases Increase-decrease fungi-virus-insect pests Increase-decrease presence of weeds Increase-decrease crop mortality
Crops Phenology & Growing patterns	Change in crops´ flowering time Change in crops´ fruiting time Change in crops´ ripening time Change in crops´ harvesting time Shifting phenology in plants Increase-decrease length of flowering season Increase-decrease length of fruiting seasons Increase-decrease length of ripening season Increase-decrease length of harvesting seasons Change in cultivation altitude
Soil degradation & fertility	Increase-decrease soil degradation Increase-decrease soil fertility Increase-decrease soil productivity Increase-decrease fertile land Increase-decrease presence of soil lichens, soil bacteria or viruses
Forest cover	Increase-decrease forest cover/ density/ deforestation Change in timber forest composition/structure Increase-decrease timber forest spp More-fewer disappear tree spp More-fewer disappear useful woody spp Increase-decrease size of woody spp Increase-decrease wilting trees Increase-decrease tree mortality More-fewer death trees
Forest fires	Increase-decrease fire frequency Increase-decrease size/extension of fires
NTFP availability & quality	Increase-decrease size of wild fruits Increase-decrease taste of wild fruits Increase-decrease availability of non-domestic fruits Increase-decrease availability of edible products Increase-decrease availability of medical plants

Pasture availability & quality	More-fewer number of grass spp Change of spp composition More-fewer number of grass spp disappeared Increase -decrease grasslands-rangeland surface Increase-decrease pasture weeds Increase-decrease duration of pasture Increase-decrease grass-forage density-height
Livestock disease	Increase-decrease livestock disease Increase-decrease livestock death More-fewer vector-borne diseases (flies-mosquitoes- ticks) More-fewer malnourished livestock More-fewer unhealthy animals Increase-decrease livestock parasites
Livestock phenology & reproduction	Increase-decrease reproduction effectiveness Increase-decrease mating frequency Change of mating-reproduction time More-fewer number of pups-offspring Increase-decrease unusual animal behaviour
Livestock productivity & quality	Increase-decrease livestock productivity (milk-meat) Increase-decrease milking periods of animals Increase-decrease weight loss of livestock
Fish stock abundance	Increase-decrease marine-river fish stocks abundance Change fish stock composition New marine-river fish spp no IAS Increase-decrease disappearance of marine-river fish spp
Fish IAS	More-fewer spp stated as invasive
Fish Disease - Mortality – Pest & Parasites	Increase-decrease fish disease-parasites Increase-decrease fish malformations Increase-decrease size of fish Increase-decrease mortality of fish
Fish Phenology / Distribution & reproduction	Increase-decrease unusual animal patterns Change in migratory time-mating time Change migratory routes Change geographical and depth distribution
Diseases	Increase-decrease incidence of human diseases (* flu, allergies, malaria, etc)
Health injuries, physical affection	Increase-decrease human health injuries (ice, weather inclemency, walking longer distance to water)
Hunger	Increase-decrease hunger frequency More-fewer number of people affected
Cultural/Spiritual/ Identity values	Increase-decrease cultural-identity-spiritual values
Trails	More-fewer problems and cuts in transport and trails communication routes

Electronic supplementary material 2

Figure 2.2. Number of observations found in the literature review by system and year of publication of the articles



Electronic supplementary material 3

Table 2.4. Research field of the web survey participants

Research field	**n**	**%**
Aerobiology	5	2,60%
Agroecology	7	3,65%
Agroforestry	2	1,04%
Agronomy	4	2,08%
Animal Production	1	0,52%
Aquaculture	1	0,52%
Atmosphere´s physics	2	1,04%
Botany /geobotany / paleobotany	13	6,77%
Climatology / Bioclimatology	3	1,56%
Coastal engineering	1	0,52%
Conservation (flora / fauna)	6	3,13%
Earth system modelling	1	0,52%
Earth´s physics	1	0,52%
Ecology	33	17,19%
Ecology (animal)	8	4,17%
Ecology (aquatic / wetlands)	4	2,08%
Ecology (evolutionary / behaviour)	7	3,65%
Ecology (forestry)	7	3,65%

Ecology (marine/ littoral)	11	5,73%
Ecology (plant)	7	3,65%
Ecophysiology	1	0,52%
Ecotoxicology	1	0,52%
Edaphology / soil ecology / soil microbiology	12	6,25%
Environmental history	1	0,52%
Environmental microbiology	1	0,52%
Environmental sciences	5	2,60%
Ethnoecology / Ethnobotany	2	1,04%
Fisheries	2	1,04%
Geochemistry/ Biogeochemistry	4	2,08%
Geography (physical geography / biogeography)	8	4,17%
Geomorphology	1	0,52%
Global change	2	1,04%
Hydrology / hydrogeology / hydromorphology	6	3,13%
Limnology	3	1,56%
Oceanography	9	4,69%
Paleontology	1	0,52%
Palynology	1	0,52%
Phytochemistry	1	0,52%
Plant physiology	2	1,04%
Social anthropology	1	0,52%
Social ecological systems (Biocultural systems/ Ecosystem services/Landscape´s social perception/ Rural development/ Societal metabolism/ Silvo-pastoral systems)	10	5,21%
Sustainability sciences	3	1,56%
Zoology (entomology/ herpetology/ mammalogy/ marine/ ornithology)	12	6,25%

Electronic supplementary material 4

Table 2.5. List of new LICCI proposed by respondents of the web survey

Sub-system	**New LICCIs proposed**	Agriculture related
Temperature	Study the practice of cabañuelas (traditional annual weather forecasting technique)	x
	Difference between the maximum and minimum temperature, since this difference is being reduced, the minimum being the one that increases the most.	
Air mases	Time of the day of extreme windy episodes	
	Proximity to the storm area	
	Name of the events	
Rainfall	In South-East Spain (Cabo de Gata) traditional farmers talk about "Cabañuelas" in the summer to predict the rainfall events of the following months	x
	Take into account the Lunar and Gregorian calendar and their time lags	
	Terraces, plowed soil	x
Soil	Changes in agricultural land management (use of vegetation cover, terracing, etc.)	x
	Compaction	
	Effect of plant and inorganic coverings	

	Differences between traditional irrigation systems.	x
	Need (frequency and quantity) of irrigation of agricultural soils	x
	Dryness of key plant species (pasture, weeds ...)	x
	Fisheries by locals as a proxy of water quality	
	The uses of water and the resource management	
	Biological indicators / Indicators of stagnant water bodies (lentic systems)	
Continental waters	Phenology of floods	
	Food from Fisheries	
	Presence of species with specific temperature ranges	
	Drinking water for cattle	
	Old pictures of lakes/rivers with different water level	
	Number of wells that are not included in the "water network"	
	Ethnocartography of fountains and springs	
Ocean - Sea	Temperature shifts in seasons of shellfish yield	
	Coastal infrastructure, beach grooming	
Snow - Ice	Old pictures of Snow cover / Glaciers / Ice-sheet	
	Presence of permanent snow (enduring from one year to another)	
Terrestrial vertebrates	Abundance of species with specific temperature ranges	
Birds	Temporary trends in population density	
No- fish marine spp	Frequency of red tides / massive proliferation of microorganisms	
	Degradation of marine habitats	
Arthropods	Interactions between species (e.g. insect-plant)	x
Wild flora	Value of use of species that are being lost	
	Changes in the use of the species	
	Changes in the potentiality of a species as invasive; degree of integration of the invasive species in the local natural environment	
Agriculture	Agricultural techniques used, handling, tilling, weeding	x
	Economic profit of rural agricultural lands	x
	Agricultural landraces used	x
	Other vegetation or practices linked to the management of those crops	x
	Crop rotations	x
	Use of hybrid crop	x
	Knowledge for the seeds´ selection to maintain traditional varieties	x
	Crops associations	x
	Traditional remedies to fight pests	x
	Changes in crop water requirements	x
	Incidence of crops (associations) in soil fertility	x
	Soil management	x
	Duration of the optimal period for tillage	x
	Information on compost production with plant residues from the farm	x
Livestock and pastures	Number of different raw materials and number of uses per material	
	Breeding changes	
	Rentability of the traditional livestock	
	Livestock numbers in extensive pastures	
	Sociological indicators	
Forestry	Traditional management practices for the prevention of fires.	
	Period when the fires take place	
	Severity of fires (destruction of mulch, subsequent erosion due to fire)	
	Socio-Economic indicators	
	Causes of fires	
	Diversity of NTFP	

Chapter III

Local perception of climate change impacts in Sierra Nevada, Spain. Analysing sociodemographic and geographical patterns

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Local perception of climate change impacts in Sierra Nevada, Spain. Analysing sociodemographic and geographical patterns

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Abstract:

While we now know well that climate change is having different impacts on various ecosystems and regions of the world, we know less how perceptions of climate change impacts vary within a population. In this study, we examine patterns or individual variation in perceptions of climate change impacts using a sample drawn from in 33 mountainous municipalities of Sierra Nevada, Spain (n=238). Overall, we found that Sierra Nevada inhabitants perceive multiple impacts of climate change, and particularly changes in the climatic and physical systems. However, we also found that such perceptions are shaped by informants' sociodemographic characteristics and geographical location. Overall, people with a personal history of bonds with the environment perceived more climate change impacts that other informants. Location is also associated to the perception of different impacts, suggesting that climate change might have differentiated impacts even at small geographical scales. Understanding such differences is important, not only to have a more complete picture of climate change impacts, but also because different perceptions might play a mayor role in mitigation and adaptations efforts.

Keywords: *Climate change impacts, indigenous and local knowledge, local perception, mountain areas, Spain.*

1. Introduction:

Climate change is having differentiated impacts on different ecosystems and regions of the world (IPCC, 2013). In their efforts to develop prediction models to understand these impacts, climate change researchers face two main challenges: the interaction of climate change with other drivers of change and the lack of a global dataset with evenly distributed local weather and environmental data. Together, these challenges result in many uncertainties in climate prediction models (Rosenzweig and Neofotis, 2013; Stone et al., 2013; Stott et al., 2010) with consequences for adaptation planning (IPCC, 2014). As a result, climate researchers –including researchers involved in the Intergovernmental Panel on Climate Change (IPCC)- have started to call for more grounded data sources to improve the accuracy of prediction models. In answer to this call, several researchers have proposed that Indigenous and Local Knowledge (ILK) has the potential to increase understanding of local climate change impacts (Alexander et al., 2011; Cramer et al., 2014; Ford et al., 2016; Hu et al., 2020). Indigenous Peoples and Local Communities (IPLC) with a historical dependency on natural resources for their livelihood are first-hand witnesses of environmental changes, which might allow them to accurately report climate change impacts on their local environments (Byg and Salick, 2009; Maldonado et al., 2016; Reyes-García et al., 2019).

Indeed, over the last decade several works have shown that IPLC perceptions of climate change impacts overlap with impacts documented in scientific records (Krupnik et al. 2010, Boillat and Berkes 2013, Savo et al. 2016, Reyes-García et al. 2019). Moreover, these works have started to form a scientific field rapidly advancing theoretically and methodologically. Theoretically, the field is moving from the idea that IPLC’s body of knowledge needs scientific validation to acknowledge its own validity and recognize that its added value comes from combining it with evidence from other knowledge systems (Armitage et al., 2011; Tengö et al., 2014; Watson and Huntington, 2014). Methodologically, the field is moving from the case study perspective (e.g., (King et al., 2008; Lefale, 2010; Mosites et al., 2018), to the development of standardized methodologies that allow a more global assessment of IPLC´s perceptions of climate change (Reyes-García et al., 2019).

A major gap in research on IPLC perceptions of climate change impacts relates to the lack of focus on intra cultural variation of such perceptions. Individual perceptions of climate change impacts can be shaped by a diversity of factors that mediate how each person relates to the environment. Such factors can range from geographical (e.g., the area mainly used by a person), to demographic (e.g., the sex of a person), or socio-economic factors (e.g., the economic activities that that the person conducts in iteration with the natural environment). Understanding such differences is important, not only to have a more complete picture of climate change impacts, but also because the differentiated perception of climate change impacts might play the mayor role in mitigation and adaptations efforts (Armah et al., 2015).

To start filling this gap, here we i) document climate change impacts perceived by rural communities in a mountainous region of Spain and ii) assess how sociodemographic and geographical patterns shape the perception of climate change impacts. We focus on a mountain area because of the important role of mountains (IPCC, 2014; Messerli, 2012; Zamora et al., 2017) and local mountain communities (Joshi et al., 2013; Postigo, 2014; Shijin and Dahe, 2015; Wang and Cao, 2015) in understanding climate change impacts. Mountains are, indeed, ideal geographic enclaves to study climate change impacts due to their altitude variation, hydrologic importance, and extreme conditions (Beniston, 2003; Nogués-Bravo et al., 2007). Climate change impacts in mountain biological systems include displacement of species towards mountaintops and declining species diversity (Pauli et al., 2012; Pounds et al., 1999), changes in vegetation composition (Walther et al., 2005), and phenological changes in fauna and flora (Inouye and Wielgolaski, 2013). Moreover, climate change impacts have also been reported to affect human systems by reducing quantity and quality of pastures (Joshi et al., 2013), increasing crop pests and livestock diseases (Postigo, 2014), extending harvesting times and increasing crops yields in other regions (Wang and Cao, 2015).

2. Methods

2.1. Study Region

We conducted research in the Sierra Nevada Natural Space (SNNS), a mountainous range with more than 172.000 hectares parallel to the Mediterranean shoreline in the south-east of Spain. Given its orographic variation, SNNS presents a great variety of ecological conditions (Castillo Martín, 1999; Raso Nadal, 2011). The region is one of the most important European hotspots for biodiversity (Blanca et al., 1998; Pérez-Luque et al., 2015), which has resulted in its protection as a Biosphere Reserve (1986), Natural Park (1989), and National Park (1999). In 2007, SNNS was also designated as a global change observatory (Zamora et al. 2016).

The SNNS geographical location makes it an ideal region to study climate change impacts. Data from the observatory shows that, since the 1970s, rainfall and snow extent and persistence have decreased (Zamora et al. 2016). Moreover, the combined effects of rising temperatures and prolonged droughts have led to shorter ice-cover periods (Pérez-Palazón et al., 2015), decreased water level, and warmer waters of high mountain lakes (Morales-Baquero et al., 2013). Reduction of snow has altered the hydrologic regime of high-mountain rivers, affecting also ecosystems and water users downstream (Jódar et al., 2017). These changes have also impacted flora and fauna resulting in up-slope range shifts of insects (Menéndez et al., 2014), flora composition and distribution (Fernández Calzado et al., 2012; Pauli et al., 2012), turnover of the bird spp composition and decreasing abundance. Moreover, such trends seem to have accelerated during the last decade (Zamora and Barea-Azcón, 2015)

Human modifications of the Sierra Nevada are documented since the Neolithic (Sánchez-Hita, 2007), but intensified since the 7th century (Muslim period), through the construction of *acequias*, i.e., water-ditches for the management of melt water favoring the infiltration and recharge of aquifers, increasing also soil protection against erosion produced by runoff water (Ruiz-Ruiz and Martín-Civantos, 2017). In the middle of the 20th century, agricultural industrialization and the rural exodus led to the abandonment of agricultural activities, a situation that, together with the reforestation with pine trees and the declaration of protected area, led to great changes in the territory (Zamora et al. 2016). Despite these changes, people working on agropastoral activities continue to rely on traditional knowledge and management techniques for their livelihood (Iniesta-Arandia et al., 2015). Recent research in the region comparing the current environmental status with the baseline reported in local proverbs suggests that people are able to perceive climate change impacts (Garteizgogeascoa et al., 2020).

2.2 Sampling

The sampling strategy included village and participant selection. To capture potential geographical differences in climate change impacts at local scale, we followed a systematic sampling to select villages for this study. Specifically, we selected villages with more than 300 inhabitants around the mountainous region inside the SNNP. Due to low population density, we grouped the selected villages into eight zones of 10 kilometers radius. A zone encompassed 3 to 5 villages. Being a mountainous area, the average altitude largely varies across zones (Figure 3.1).

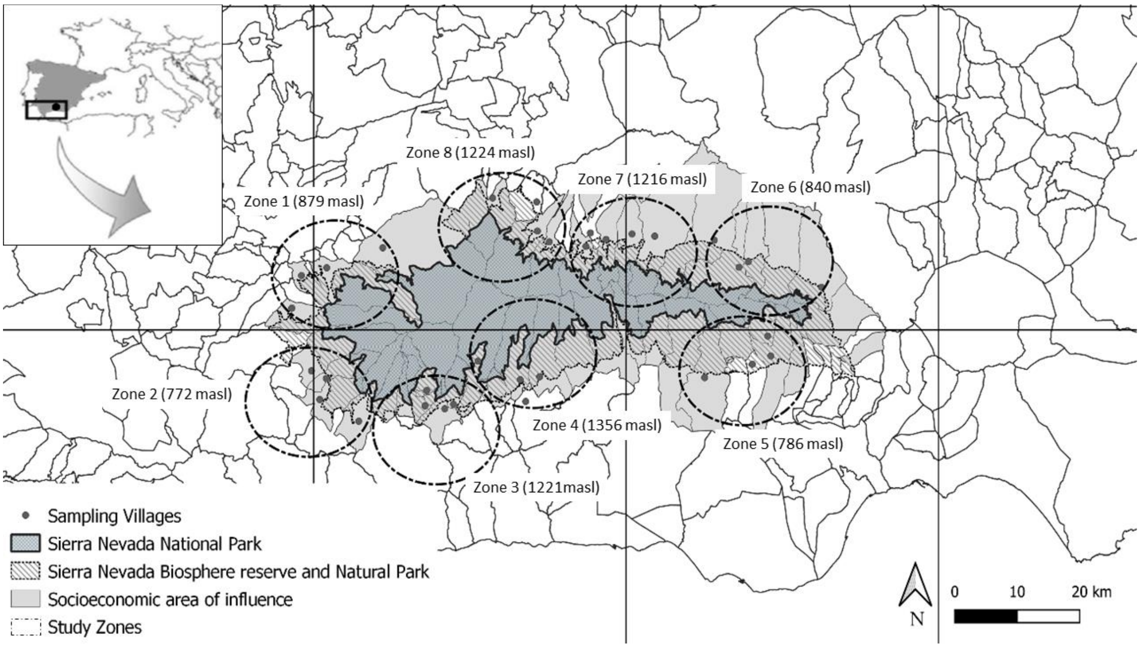

Figure 3.1. Map of study region. Dots represent the 33 sampled villages. Circles represent the eight study zones: zone 1: Granada´s surroundings, zone 2: Lanjarón and Lecrín Valley, zone 3: Poqueira Ravine, zone 4: Trevélez and Bérchules Ravines, zone 5: Ohanes Ravine, zone 6: Nacimiento Valley, zone 7: La Calahorra Valley, zone 8: Marquesado del Cenete. Number in brackets ( ) represents the average m.a.s.l. of villages in a zone.

To capture potential socio-economic differences, we followed a convenience stratified sampling (Shively, 2011) and selected individuals with different livelihood strategies. Criteria for inclusion in the sample were to have lived 25 years or longer in the village of residence and to have a profession directly or indirectly related to agropastoral activities. For our stratification, we considered the following professions: *farmers, shepherds, ranchers, agricultural ranchers* (farmers who also have livestock), *beekeepers* and *others*. The last group included people who performed agropastoral activities, not as a main economic activity, but as a secondary economic activity or for self-consumption. Interviewee selection was conducted using different techniques. We held a meeting with the mayor of each village to explain the project and meet members of different associations. Through these representatives, we contacted other members of the associations in the same or other zones. To find a balanced number of representatives regarding professions and to increase gender variability, we also approached potential respondents by directly visiting farms and agricultural fields located on the outskirts of the villages. Overall, we conducted 238 questionnaires in 33 villages from June to December 2018.

Our data collection procedures received the ethical approval of the Autonomous University of Barcelona (CEEAH-3581). We asked participants to sign a free, prior and informed consent form before starting data collection.

2.3 Survey

The survey consisted of two sections: respondents' (i) sociodemographic information and (ii) perceived local indicators of climate change impacts.

In the first part of the survey, we collected information on sociodemographic characteristics of individuals including profession, age, gender, school level, parents' and grandparents' origin, years of experience in agropastoral activities, and number of activities conducted in nature.

Profession was coded as *farmers, shepherds, ranchers, beekeepers, agricultural ranchers,* and *others*. We also created the dummy variable *primary sector* that differentiates respondents in the category *others* from the rest of informants. Age was collected in years, but later grouped into 15-year ranges (25 to 39 years; 40 to 54 years; 55 to 69 years; 70 to 84 years; > 85 years). Respondent's school level was coded into four categories (0= without schooling, 1= primary school completed, 2= secondary or vocational education completed, and 3= bachelor or higher studies completed). We also created a dummy variable, *formal schooling,* to differentiate people without any formal studies from others. We collected information on parent's and grandparent's origins because family origin and migration status affect individual's local knowledge (Brandt et al., 2013; Pirker et al., 2012). Finally, we collected information on the number of activities conducted in nature, counting as separate activities agriculture, livestock, beekeeping, hunting, wood and non-timber forest products collection, as this is a good proxy for the level of interaction with the environment (Reyes-García et al., 2009). We also collected information on the informants' residence zone.

In the second part of the survey, we asked informants to report environmental changes noted when comparing the current state of the environment with the situation 25 years ago. To select environmental changes to include in our survey, we relied on a literature review on local observations of climate change impacts and on semi-structured interviews. Specifically, from an initial list of local observations of environmental changes validated by climate change researchers, we selected those that could have been observed in the region (García-del-Amo et al., 2020). We confirmed the local occurrence of these impacts by consulting literature on the study area and conducting interviews with 20 elderly people and 10 local experts. The final list for the survey included 95 local indicators of climate change impacts (LICCI) affecting elements of the climatic (n=12), the physical (n=11), the biological (n=15), and the human systems (n=8) (Table 3.2 SM1). For each of the indicators selected, we asked respondents *"Could you tell me, if you have noticed any changes in {LICCI} in this area during the last 25 years?"*

3. Analysis

We calculated the number of impacts perceived by each informant. For each LICCI in our survey, responses could be coded as 0= the person considered there was no change, 1= the person perceived the change, and 2= person did not know.

We start the analysis by exploring the impacts most commonly perceived by informants. To do so, we calculated the percentage of people perceiving each of the 95 impacts proposed in the survey, and analysing results in relation to different impacted elements of the climatic, physical, biological, and human systems. To get a deeper understanding of impacts perceived in primary sector activities, we analyzed impacts in the human system separately and differentiating across professions. For example, to analyze perceptions of impacts in crops, we only considered the opinion of farmers and agricultural ranchers (n=91); to analyze perceptions of impacts in pastures and livestock we only used the sample of shepherds, ranchers and agricultural ranchers (n=78), and to analyze perceptions of impacts on bees we only considered the sample of beekeepers (n=31).

The second part of the analysis consisted in exploring how sociodemographic and geographic factors shape individual perceptions of climate change impacts. We compared the percentage of respondents perceiving and not perceiving changes across professions, age, gender, school level, and geographic zones. Because the sample did not meet the conditions of normality and homoscedasticity, for our calculations we used a series of Kruskal-Wallis nonparametric tests.

To assess the degree to which different variables shaped respondent's perceived climate change impacts, we created five indices that, basically, counted the total number of impacts perceived

(LICCI Index) and the number of impacts perceived from each system (i.e., *Climatic Index, Physical Index, Biological Index, Human Index)*. We then ran a set of multivariate regressions using our sociodemographic variables (i.e., profession, age, gender, school level, parents´ and grandparents´ origin, and activities conducted in nature) as potential explanatory variables of our five indices (i.e., dependent variables). We used Poisson regressions because our variables are discrete with non-negative integer values (Cameron and Trivedi, 1998). To test the robustness of our results, we ran a set of similar models with the following changes: excluding women in the sample, including clusters by zones, using our categorical variable "age range", using the dummy for "education", and using a statistical linear model. In all the analyses, we report p-values < 0.05 as indicator of statistical significance. All statistical analyses were carried out with the STATA program version 13 and the statistical applications of the Microsoft EXCEL program 2016 version.

4. Results

We obtained responses from farmers (n=66), shepherds (n=40), ranchers (n=13), beekeepers (n=31), agricultural ranchers (n=25), and others (n=63). Women composed only 6.7% of the sample, as most women approached refused to participate. Most respondents (76.9%) had between 40 and 69 years of age and only 10.5% had a university degree.

4.1. Perceptions of climate change impacts

Overall, more people perceived changes in the climatic and physical systems than in the biological and human systems (Figure 3.2). *Changes in mean rainfall* (perceived by 97.5% of respondents), *changes in seasonal rainfall* (93.3%), *changes in snowfall and snow cover (91.9%),* and *changes in terrestrial fauna abundance (91.9%)* were the elements in which impacts were more often reported. Eight of the elements most often impacted belong to the climatic system. More than 85% of respondents perceived changes in five elements of the physical system.

Perceptions of changes in elements of the biological system show the greatest disparity of opinions between respondents. *Changes in abundance of terrestrial fauna* (mammals, birds, reptiles, amphibians, and insects) (91.9%), *changes in vegetation abundance,* represented by changes in riverside vegetation and trees (84.9%), and *changes in the appearance of pests, diseases and mortality of wild flora* (81.9%) were perceived by most interviewees. But a more detailed analysis of impacts in the biological system showed differences between different animals. Thus, respondents perceived changes in the distribution (67.2%) and appearance of diseases in mammals (77.3%), mainly scabies in wild boards (*Sus scrofa*) and mountain goat (*Capra pyrenaica*). Informants from Granada´s surroundings´ claimed to have seen a mountain goat adult male in the town square before dusk. "This never happened before". *Changes in bird's abundance* were perceived by most of respondents (95.4%) and reports of the appearance of new species of birds were also frequent (75.2%). Many respondents indicated a large increase of starlings (*Sturnus vulgaris*) in their area and several interviewees claimed that they did not remember having seen them when they were young. Differently, more than 75% of informants reported not being aware of changes in fish species other than changes in fish abundance. For example, some of the oldest interviewees told us that when they were young, people used to "fish by watering", because trout were so abundant in the river that many got into the *acequias* and when they opened the floodgates to irrigate the fields, trout ended up in the crops. A few respondents reported changes in fish size, reporting a size increase. In the words of an informant, "Now we are not allowed to fish trout, so the biggest ones eat most of the fingerlings and the population structure is changing with more adult members and less young fish." *Changes in abundance of insects* also was perceived by a large number of respondents (85.7%), including *changes in abundance of wild hives* (90.7%). Many respondents also perceived *changes in the activity period of insects* (73.9%). Some shepherds and ranchers claimed that nowadays their livestock have problems with fleas and ticks during almost all the seasons (Figure 3.3)

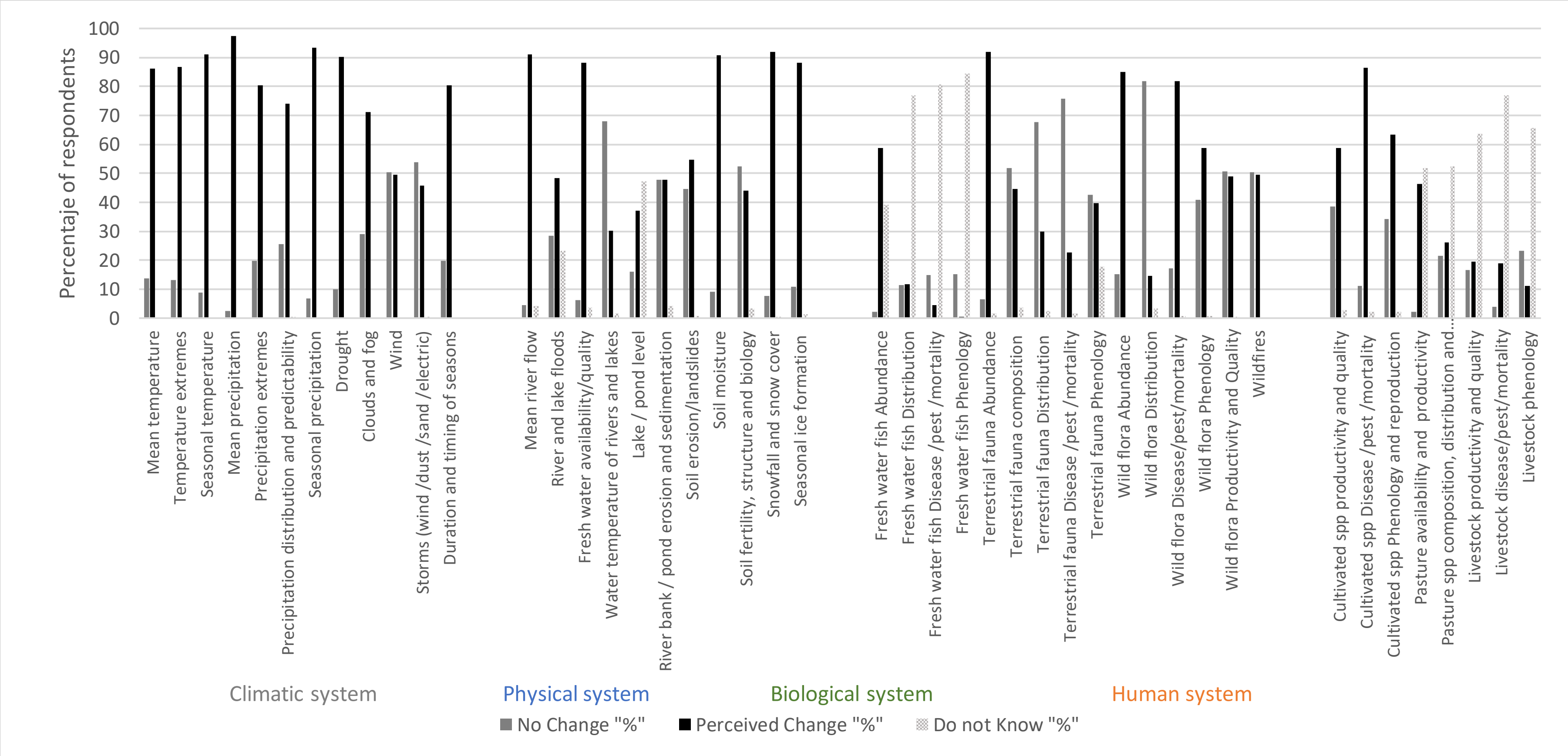

Figure 3.2. Perception of changes perceived by respondents on the climatic, physical, biological and human systems.

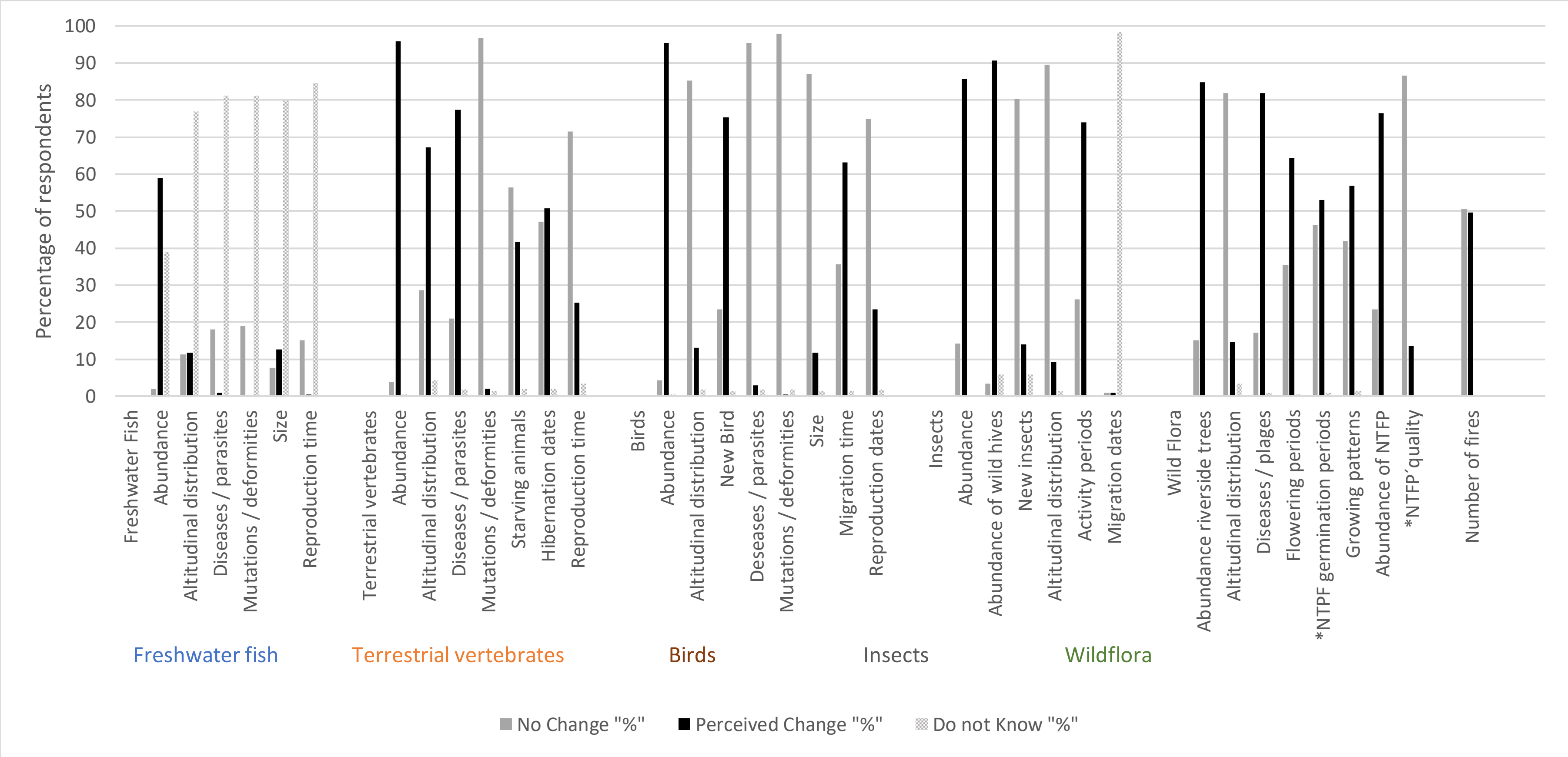

Figure 3.3. Perception of changes perceived by respondents on each Local Indicator of Climate Change Impacts (LICCI) included in the biological system. *NTFP : non timber forest products.

Finally, when analysing the results of the human system, *changes in crop pests, diseases and mortality* (86.6%) was the impact perceived by most respondents (Figure 3.2). However, the specific analysis of impacts on elements the human system considering only respondents directly dependent on agropastoral professions showed that, for this set of respondents, *changes in the availability of pastures* and *changes in livestock and bees' pest and diseases* were also frequently perceived (Figure 3.4; Table 3.3.SM1).

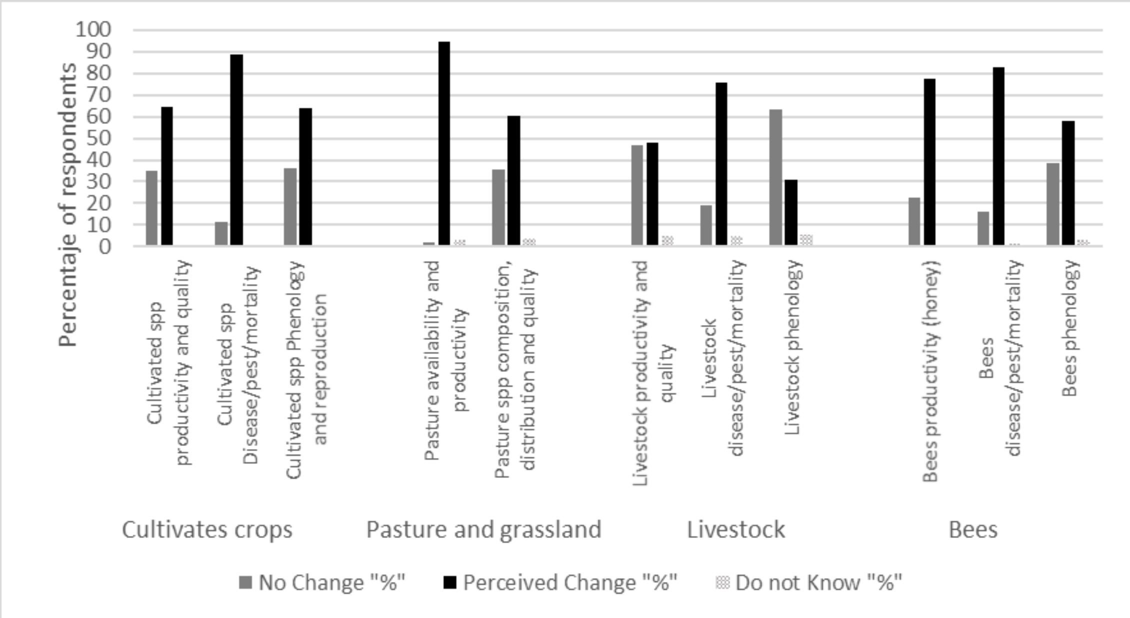

Figure 3.4. Perception of changes in the human system perceived by respondents with professions directly dependent of agropastoral activities. Changes in cultivated crops represent perceptions of farmers and agricultural ranchers (n=91); changes in pasture and grassland and changes in livestock represent perceptions of shepherds, ranchers and agricultural ranchers (n=78); and changes in bees represent perception of beekeepers (n=31).

4.2. Sociodemographic and geographic correlates of climate change impacts perception

On average, respondents reported perceiving 52.4 out of the 95 impacts included in the survey. Shepherds (56.4) and agricultural ranchers (56.2) perceived more climate change impacts than people with other occupations did (χ^2 = 21.43; p= 0.001). Farmers (50.3) and people with professions other than agropastoral activities (49.2) perceived the least number of impacts. Groups of respondents in the ranges between 40 to 54 and 55 to 69 years of age also perceived more impacts than people in other age-range groups (χ^2 = 9.54; p= 0.049). Men and women perceived similar number of impacts. People without formal studies (53.1) or with only primary education (53.9) perceived more impacts than the rest of informants. Finally, respondents living in Granada´s surroundings, Trevélez and Bérchules Ravines and Ohanes Ravine perceived more impacts than respondents in other zones did (Table 3.1).

Table 3.1. Average LICCI index, by profession, sociodemographic characteristics and geographical location (Zones)

Variable	Group (Profession)	Farmers		Shepherds		Ranchers		Beekeepers		Agricultural ranchers		Others		Total *(n)* *Average LICCI Index*	
		n	***Average LICCI Index***	***n***	***Average LICCI Index***	***n***	***Average LICCI Index***	***n***	***Average LICCI Index***	***n***	***Average LICCI Index***	***n***	***Average LICCI Index***		
Age range	25-39	5	41	1	40	-	-	2	50.5	1	71	4	45	***(13)***	***45.9***
	40-54	21	52.3	12	58.2	8	53.9	15	52.9	8	55.7	21	51.7	***(85)***	***53.6***
	55-69	20	52.7	22	55.6	5	58.9	12	54.7	9	56.9	30	49	***(98)***	***53.2***
	70-84	18	48.3	5	59	-	-	2	58.5	6	53.3	8	45.1	***(39)***	***50.3***
	85 and over	2	47.5	-	-	-	-	-	-	1	57	-	-	***(3)***	***50.7***
Study Level	Without formal studies	19	48.5	15	57.9	1		2	62	6	55.2	5	46.8	***(48)***	***53.1***
	Primary school	25	54.9	17	56.3	8	53.6	9	55.7	18	55.8	25	49.4	***(102)***	***53.9***
	Secondary and vocational education	15	49.4	8	53.9	3	61.7	15	54.1	1	71	21	48.3	***(63)***	***51.6***
	Bachelor, Master and Ph.D.	7	40.9	-		1		5	46.6	-	-	12	51.1	***(25)***	***46.9***
Gender	Female	3	46	3	65.3	-	-	5	57.2	1	51	4	42.2	***(16)***	***52.5***
	Male	63	50.5	37	55.7	13	55.8	26	53.2	24	56.5	59	49.6	***(222)***	***52.4***
Zone	Granada´s surroundings	9	53.1	6	56.8	2	64	6	54	5	60.2	5	42.4	***(33)***	***54.1***
	Lanjarón and Lecrín Valley	4	48.5	4	54.2	1	45	6	49.7	4	55	9	47.1	***(28)***	***49.9***
	Poqueira Ravine	10	53.2	3	60.7	1	66	3	49	-	-	13	49.3	***(30)***	***52.3***
	Trevélez and Bérchules ravines	12	52.4	1	48	3	61.7	2	71	5	55.8	8	52.1	***(31)***	***54.8***
	Ohanes ravine	5	52.6	8	62.4	1	52	3	60.7	4	57.5	7	51.9	***(28)***	***56.7***
	Nacimiento valley	6	49.5	4	44.5	-	-	5	50.2	5	56	9	58.1	***(29)***	***52.7***
	La Calahorra Valley	10	46	6	58.7	1	40	6	54.2	1	63	5	41.8	***(29)***	***50***
	Marquesado del Cenete	10	46.9	8	55.1	4	52.2	-	-	1	33	7	44.1	***(30)***	***48.7***
Total *(n)* *Average LICCI Index*		***(66)***	***50.3***	***(40)***	***56.4***	***(13)***	***55.8***	***(31)***	***53.8***	***(25)***	***56.2***	***(63)***	***49.2***	***(238)***	***52.4***

We found several associations between sociodemographic characteristics of informants and perceptions of climate change impacts, as measured by our indices (Table 3.2). When considering the total number of impacts perceived, we found that shepherds and agricultural ranchers perceived more impacts than people with other professions did (Table 3.2, Column 1). Age displays an inverted-U association with the LICCI index, so although the score of the LICCI index is higher with age, after a certain point, the relation is negative. A person's level of schooling had a negative association with the number of impacts perceived, although the difference was statistically significant only for the group of respondents who reached university. We also found that, while having grandparents born in Sierra Nevada showed a positive association with the LICCI index, the association for having parents born in Sierra Nevada was negative. We also found a positive and statistically significant association ($p < 0.05$) between the number of impacts perceived and the number of primary activities performed in nature by a respondent. Finally, location also showed a statistically significant association with the number of impacts perceived, with informants from Ohanes ravine perceiving more impacts than informants from other zones did.

Table 3.2. Results of Poisson regression showing sociodemographic correlates of climate change impacts perceived (n=238)

	LICCI Index	Climatic Index	Physical Index	Biological Index	Human Index
Profession (*farmers* omitted category)	.	.	.	.	.
Shepherds	0.0862***	0.0385	0.0226	0.0236	0.4175***
	(0.0297)	(0.0569)	(0.0545)	(0.0561)	(0.0774)
Ranchers	0.0618	0.0345	0.0379	-0.0082	0.2994***
	(0.0430)	(0.0826)	(0.0799)	(0.0818)	(0.1082)
Beekeepers	0.0347	-0.0148	-0.0397	-0.0037	0.3377***
	(0.0329)	(0.0638)	(0.0613)	(0.0617)	(0.0833)
Agricultural ranchers	0.0766**	0.0610	0.0245	0.0026	0.3564***
	(0.0338)	(0.0650)	(0.0621)	(0.0640)	(0.0870)
Other professions	-0.0163	-0.0089	-0.0585	-0.0253	0.0737
	(0.0267)	(0.0505)	(0.0489)	(0.0498)	(0.0731)
Age	0.0223***	0.0113	0.0254**	0.0315***	0.0254
	(0.0064)	(0.0119)	(0.0119)	(0.0121)	(0.0170)
Age^2	-0.0002***	-0.0001	-0.0002**	-0.0003***	-0.0003
	(0.0001)	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Female	-0.0242	0.0544	0.0329	-0.1212	-0.1057
	(0.0382)	(0.0709)	(0.0695)	(0.0744)	(0.1012)
School level (*no formal studies* omitted category		.	.	.	.
Primary school	-0.0068	0.0068	-0.0244	0.0167	-0.0449
	(0.0275)	(0.0525)	(0.0501)	(0.0520)	(0.0723)
Secondary and vocational studies	-0.0288	-0.0099	-0.0725	-0.0053	-0.0188
	(0.0339)	(0.0648)	(0.0625)	(0.0638)	(0.0884)
Bachelor, Master and PhD	-0.0960**	-0.0984	-0.0995	-0.0983	-0.0640
	(0.0436)	(0.0833)	(0.0799)	(0.0821)	(0.1142)
Parents born in Sierra Nevada	-0.1095**	-0.1976**	-0.0685	-0.1205	-0.0065
	(0.0514)	(0.0987)	(0.0944)	(0.0959)	(0.1348)
Grandparents born in Sierra Nevada	0.0533**	0.1055**	0.0347	0.0425	0.0172
	(0.0246)	(0.0479)	(0.0450)	(0.0460)	(0.0630)
Years of experience	-0.0016	-0.0019	-0.0012	-0.0019	-0.0009
	(0.0011)	(0.0020)	(0.0020)	(0.0021)	(0.0031)
Number of activities in nature	0.0422***	0.0211	0.0201	0.0531***	0.1025***
	(0.0099)	(0.0190)	(0.0185)	(0.0186)	(0.0256)
Zone Granada´s surroundings	0.0745**	-0.1159	0.0711	0.2602***	0.1060
	(0.0377)	(0.0710)	(0.0697)	(0.0717)	(0.1003)
Zone Lanjarón and Lecrín Valley	0.0007	-0.1638**	0.0167	0.0942	0.1159
	(0.0406)	(0.0767)	(0.0749)	(0.0777)	(0.1054)
Zone Poqueira Ravine	0.0483	-0.0490	0.0310	0.1786**	0.0437
	(0.0390)	(0.0718)	(0.0723)	(0.0741)	(0.1063)
Zone Trevélez and Bérchules Ravines	0.0979**	-0.0355	0.0666	0.1770**	0.2818***
	(0.0385)	(0.0715)	(0.0714)	(0.0743)	(0.1012)
Zone Ohanes Ravine	0.1038***	-0.0230	0.1491**	0.1998***	0.1018
	(0.0389)	(0.0721)	(0.0710)	(0.0753)	(0.1049)
Zone Nacimiento Valley	0.0421	-0.1390	0.1015	0.1140	0.1490
	(0.0397)	(0.0747)	(0.0723)	(0.0765)	(0.1043)
Zone La Calahorra Valley	0.0116	-0.0585	0.0535	0.0400	0.0351
	(0.0391)	(0.0717)	(0.0715)	(0.0764)	(0.1053)
_cons	3.1822***	2.3206***	1.9183***	1.6279***	0.8678
	(0.1971)	(0.3705)	(0.3688)	(0.3717)	(0.5147)

We conducted a similar analysis using our other measures of perceived impacts as dependent variables. For the Climatic Index, only the variables that capture whether the informant had parents and grandparents born in Sierra Nevada were associated to the number of impacts perceived displayed in the climatic system. We also found that people from Lanjarón and Lecrín Valley perceived fewer impacts in the climatic system than people from other zones (Column 2, Table 3.2). Respondent's age and living in Ohanes ravine had a positive association with climate impacts perceptions in elements of the physical index (Column 3, Table 3.2). In particular, respondents from Ohanes ravine perceived more impacts related to the availability of hydric resources than respondents from other zones. An informant told to us: "when I was a child, the spring of my village had a flow of 'two bodies' [a local measure of volume] and now there is less than 'one arm'". Respondent's age, number of activities performed in nature, and location (i.e., living in Granada´s surroundings, Poqueira ravine, Trevélez and Bérchules ravines and Ohanes ravine) bear a positive association with the number of impacts perceived in the biological system (Column 4 in Table 3.2). Finally, an informant's profession and total number of activities' performed in nature were associated with the number of climate change impacts perceived in the human system. Particularly, shepherds, agricultural ranchers, beekeepers and ranchers perceived more climate change impacts in the human system than farmers (Column 5, Table 3.2). People living in Trevélez and Bérchules ravines also perceived more impacts in the human system than people in other zones.

In our analysis to test the robustness of our main model, we only found small deviations from our main results (Table 3.4 SM2). Thus, in this analysis, we found that the negative association of having parents born in Sierra Nevada disappears when we only use the subsample of men. We also found that, when using age in ranges the group of people over 85 years had a lower score in the LICCI index than other groups. Finally, when replacing the categorical variable "study-level" by the dummy variable "*Formal studies"* the negative association of education with the LICCI index disappears.

5. Discussion

Findings from this work show that, although Sierra Nevada inhabitants perceive multiple impacts of climate change, their perceptions are shaped by sociodemographic characteristics and geographical location.

Before discussing the importance of these results, we present some sampling and measurement biases that call for caution in interpreting them. We acknowledge that our sample might be biased. Although we aimed for a balanced sample, due to particularities of the study region, our database does not have a balanced distribution among people from different age classes, genders, and professions. Youth migration and the abandonment of some professions make some age groups and professions more common than others; local cultural norms result in higher refusal to participate among women than among men; and orographic and climatic differences result in unbalanced geographical concentration of some professions. Despite the apparent imbalance, however, our sample likely reflects the population distribution across activities and zones. Our results might also be affected by measurement errors resulting from informants providing –voluntarily or involuntarily- inaccurate information, as it happens when discussing about sensitive issues or referring to past times (Armah et al., 2015). Finally, an important caveat of our results relates to people's difficulties in identifying drivers of change. As elsewhere, in our study region several other drivers of change interact with climate change generating environmental impacts. In our survey, we asked about environmental changes potentially driven by climate change, but as we did not ask particularly about the drivers of change, the role of climate change as driver might be overestimated.

In this work, we found that Sierra Nevada inhabitants are aware of multiple environmental changes in the region, particularly changes in the climatic and physical systems, attributable to climate change. Overall, the finding concords with literature reviews of IPLC's observations of climate change impacts (Reyes-García et al., 2019; Savo et al., 2016), including recent research in the region (Garteizgogeascoa et al., 2020). Interestingly, among the impacts locally perceived, changes directly related to the water-cycle (e.g., changes in rainfall, freshwater availability, ice and snow) were reported by most informants, as it is also the case in other mountain regions (Joshi et al., 2013; Klein et al., 2014; Postigo, 2014; Shijin and Dahe, 2015). Indeed, Sierra Nevada has experienced a great decrease in water resources during the last century (Jódar et al., 2017) and changes in rainfall trends during the last decades, with less rainy summers (Ruiz Sinoga et al., 2011), dryer and longer autumns compared with 50 years ago (Machado et al., 2011), and shorter snow periods (Bonet et al. 2016). Although some changes might be difficult to detect without adequate instruments (Stone et al., 2013), temperature, rainfall and wind are important elements in the performance of agropastoral activities, for which local people are generally attentive to them (Alamgir et al., 2014; Boillat and Berkes, 2013; Postigo, 2014).

It is worth noticing that, while climate change experts consider the documentation of observations of climate change impacts in the biological system as essential for bridging scientific and local knowledge systems (García-del-Amo et al., 2020), fewer people perceived impacts on the biological system than on the climatic or physical. The impacts in the biological system more often perceived were changes in abundance of fauna and flora, changes in wild flora pests and changes in mammals and birds spp., as it has also been documented elsewhere (Irfanullah and Motaleb, 2011; Joshi et al., 2013). Differently, informants reported few impacts in freshwater fish, a finding that we attribute to fishing prohibition with the declaration of the national park (1999), with the consequent restriction of traditional activities and erosion of local knowledge (Fox et al., 2009; Santos and Sampaio, 2013). Changes in insect behaviour were also commonly perceived by our respondents, also matching findings from other studies (Chaudhary and Bawa, 2011; Lamsal et al., 2017; Postigo, 2014). For example, shepherds perceived changes in the distribution and phenology of insect spp. (e.g., fleas, ticks, horseflies, wasps and bees), as it has also been reported by researchers from the Global Observatory of Sierra Nevada (Hódar and Zamora 2004, Illán et al. 2012, Menéndez et al. 2014). Informants also perceived changes in the human system, including changes in crop pests and changes in pastures quality and availability, impacts also reported by other mountain pastoral communities (Below et al., 2015; Boillat and Berkes, 2013; Klein et al., 2014; Shukla et al., 2016; Wang and Cao, 2015). An important implication of this finding is that, because some changes are more easily documented in local knowledge system (e.g., some biological changes, or changes in important elements for productive activities), they could be the basis for efforts to explore synergies between local knowledge and science.

The second important finding of this work is that perceptions of climate change impacts are patterned by respondents´ sociodemographic characteristics. Particularly, variables capturing respondents' bonding with the territory (i.e., number of activities performed in nature, grandparents being born in Sierra Nevada, age) showed a positive association with the number of climate change impacts reported by the person, whereas schooling, a variable that often proxies for local knowledge erosion (Benyei et al., 2020; Iselin, 2011; Reyes-García et al., 2010), showed a negative association. Independently of their profession, the number of activities that an informant performs in nature was directly related with the number of impacts perceived. Moreover, in consonance with this finding, we also found that shepherds and agricultural ranchers perceived more impacts than people with other professions, probably because their activities demand long periods of time in nature alone, observing and understanding the environment, which likely attune their perception of changes. For example, shepherds in our study site predicted the abundance of the coming rains by looking at the orientation of digger wasp nests or regarding the level of blooming and fruiting of rosehip spp. Indeed, similar results about shepherds' knowledge have been found with Spanish transhumant shepherds, who showed higher levels of ILK than shepherds with their herd settle in the same area along the year (Oteros-Rozas et al., 2013), communities in Kenya (Bollig and Schulte, n.d.) or Sami herders in Finland (Riseth et al., 2011). The importance of bonding with the territory in shaping respondents' perceptions of climate change impacts was also reflected in the association found with the variable that captured whether the informant had grandparents born in Sierra Nevada and age. It is worth noticing that we actually found a negative association between the number of impacts perceived and having parents been born in the area, that might actually reflect ILK erosion due to migration to other areas (Brandt et al., 2013; Ma et al., 2019), compared with people from families with more than a century of permanence in Sierra Nevada. In a similar note, age does not show a linear association with the number of climate change impacts perceived, as the eldest respondents perceived fewer impacts. We argue that the finding might just reflect that old informants are less active, for which they might not be updating their knowledge of subtle changes as frequently as those who continue actively working (Klein et al., 2014; Oteros-Rozas et al., 2013). The finding could also reflect cognitive degeneration (Bermejo-Pareja et al., 2008).

In addition to personal characteristics, respondent's location also shaped the number and type of climate change impacts reported. We argue that, while this finding might reflect particular variations in perceptions, it is more likely that it reflects differentiated geographical climate change impacts. For example, people in Ohanes Ravine reported more impacts in the physical system than people in other areas. The Ohanes Ravine is located in the east-south region, far from the last snowfields of the summer and in an area with a lower altitude compared with other zones. Thus, the decrease of snowfalls and snow cover has been more intense in this area than in other zones, which directly affects rivers' flow and duration, soil moisture and freshwater availability. Similarly, respondents in Trevélez and Bérchules Ravines reported more impacts in elements of the human system, because of their involvement with agriculture. In this zone, villages are at high elevation, with secured access to water, and close to the snowfields that remain the longest at summer. As informants reported, temperature increase has allowed them to lengthen their agricultural production season by almost two months and without facing the proliferation of pest due to the high altitude (1500-2000 masl). In the same line, people in Lanjarón and Lecrín valley perceived less impacts in the climatic system than people in other zones, probably due to the local effect of a big dam built in this zone 16 years ago, which acts as a buffer decreasing high summer temperatures, generating a microclimate (Degu et al., 2011; Miller, 2005). Finally, changes in the biological system were more often perceived in villages located in the middle of the mountain slopes and their municipality borders extend up to 3000 masl. Respondents in these communities perceived changes in abundance and fauna distribution and argued that damages in crops and orchards have increased due to the lack of food in the mountain for wild boars and goats, as a consequence of decreased rainfall and land use change generated by pine reforestation (Zamora et al., 2016). Beyond the details, our result suggests that climate change impacts can be different even at very local scales, particularly if they are boosted by other drivers of change. The finding emphasizes that more local-based data is needed to improve our knowledge and develop accurate climate change models and adaptation measures (Cramer et al., 2014; Ford et al., 2016; Reyes-García et al., 2019; Xu et al., 2009).

6. Conclusion

The single most important finding from this work is that, although Sierra Nevada inhabitants perceive multiple impacts of climate change, perceptions are shaped by their sociodemographic characteristics, particularly bonding to the territory, and geographical location. The finding that social characteristics shape local perceptions of climate change impact, warns for caution when referring to local knowledge systems, as there might be important variations within individuals in a same group. The finding that impacts are differently perceived even at a very local scale, highlight the need to incorporate ILK in climate change research and engage IPLC in developing local policies for management and climate change adaptations.

Compliance with ethical standards

This research received the approval of the Ethics committee of the Autonomous University of Barcelona (CEEAH 3581 and CEEAH 4781).

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Journal: Regional environmental change

Local perception of climate change impacts in Sierra Nevada, Spain. Analysing sociodemographic and geographical patterns

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Electronic supplementary material 1

Table 3.3. SM1. Percentage of respondents perceiving each Local Indicator of Climate Change Impacts (LICCI) and impacted elements proposed in the survey. Differences between zones and livelihood calculated with Kruskal-Wallis test. Differences between respondents belonging to the primary sector and others calculated with Mann-Whitney test.

Subsystem	Impacted Element	LICCI	No Change		Change		Don´t Know		Zone		Livelihood		Primary sector	
			n	%	n	%	n	%	X²	p	X²	p	U	P
Climatic system														
TEMPERATURE	Mean temperature	Change mean temperature	10	4,20	228	95,80	0	0,00	10,1002	,1830	3,2625	0,6596	5470,5	,796
		Change frequency of unusual temperature	56	23,53	182	76,47	0	0,00	24,3031	0,0010*	3,2045	0,6685	5253,5	,452
		Average - Mean temperature	**33**	**13,87**	**205**	**86,13**	**0**	**0,00**	**29,8049**	**0,0001***	**3,3723**	**0,6428**	**5340,5**	**,627**
	Extreme temperature	Change number of extremely cold days	14	5,88	224	94,12	0	0,00	4,5128	0,7192	4,5515	0,4730	5309,5	,288
		Change number of extremely hot days	35	14,71	203	85,29	0	0,00	3,2045	0,8655	5,5706	0,3503	5306,0	,473
		Change frequency of heat waves	45	18,91	193	81,09	0	0,00	18,6091	0,0095*	3,3857	0,6407	5285,0	,474
		Average - Extreme Temperature	**31**	**13,17**	**207**	**86,83**	**0**	**0,00**	**6,9893**	**0,4300**	**2,2399**	**0,8151**	**5453,5**	**,874**
	Seasonal temperature	Change frequency of heat or cold periods discordant with the time of the year	21	8,82	217	91,18	0	0,00	9,0848	0,2466	5,0572	0,4089	5341,0	,456
		Average - Seasonal temperature	**21**	**8,82**	**217**	**91,18**	**0**	**0,00**	**9,0848**	**0,2466**	**5,0572**	**0,4089**	**5341,0**	**,456**
PRECIPITATIONS	Mean precipitation	Changes number of rainy days	6	2,52	232	97,48	0	0,00	4,2382	0,7520	4,1279	0,5311	5463,5	,700
		Average - Mean precipitation	**6**	**2,52**	**232**	**97,48**	**0**	**0,00**	**4,2382**	**0,7520**	**4,1279**	**0,5311**	**5463,5**	**,700**
	Extreme precipitation	Change number of extreme rainfall days	47	19,75	191	80,25	0	0,00	25,3627	0,0007*	4,6480	0,4603	4970,0	,093
		Average - Extreme precipitation	**47**	**19,75**	**191**	**80,25**	**0**	**0,00**	**25,3627**	**0,0007***	**4,6480**	**0,4603**	**4970,0**	**,093**

	Precipitation distribution, variability and predictability	Change frequency of unpredictable rainfall	61	25,63	176	73,95	1	0,42	11,4695	0,1194	2,8377	0,7250	5204,5	,387
		Average - Precipitation distribution, variability and predictability	**61**	**25,63**	**176**	**73,95**	**1**	**0,42**	**11,4695**	**0,1194**	**2,8377**	**0,7250**	**5204,5**	**,387**
	Seasonal precipitation	Change the amount of rainfall per season	16	6,72	222	93,28	0	0,00	15,8092	0,0269*	5,6189	0,3451	5183,5	,106
		Average - Seasonal precipitation	**16**	**6,72**	**222**	**93,28**	**0**	**0,00**	**15,8092**	**0,0269***	**5,6189**	**0,3451**	**5183,5**	**,106**
	Drought	Change frequency of drought periods	26	10,92	212	89,08	0	0,00	9,3845	0,2262	10,0149	0,0748	4784,5	,004*
		Change the length of drought periods	21	8,82	217	91,18	0	0,00	7,5956	0,3696	3,7058	0,5925	5222,0	,207
		Average - Drought	**24**	**9,87**	**215**	**90,13**	**0**	**0,00**	**10,5855**	**0,1577**	**9,2264**	**0,1004**	**4859,0**	**,0126**
	Clouds and fog	Change number of fogy days	69	28,99	169	71,01	0	0,00	20,2657	0,0050*	12,5265	0,0282*	4592,0	,0124*
		Average - Clouds and fog	**69**	**28,99**	**169**	**71,01**	**0**	**0,00**	**20,2657**	**0,0050***	**12,5265**	**0,0282***	**4592,0**	**,0124***
AIR MASSES	Wind	Change wind speed	143	60,08	95	39,92	0	0,00	21,9817	0,0026*	3,5186	0,6206	5376,0	,7313
		Change number of windy days	97	40,76	141	59,24	0	0,00	15,7573	0,0274*	1,4550	0,9182	5236,0	,4881
		Average - Wind	**120**	**50,42**	**118**	**49,58**	**0**	**0,00**	**22,7456**	**0,0019***	**2,2638**	**0,8116**	**5243,5**	**,5423**
	Storms	Change number of sand or dust storms	128	53,78	109	45,80	1	0,42	39,7195	0,0000*	9,1349	0,1038	5495,0	,9655
		Average - Storms	**128**	**53,78**	**109**	**45,80**	**1**	**0,42**	**39,7195**	**0,0000***	**9,1349**	**0,1038**	**5495,0**	**,9655**
SEASONS	Duration and timing of seasons	Change the length of seasons	22	9,24	216	90,76	0	0,00	9,1047	0,2452	1,8849	0,8648	5372,5	,5515
		Change transition speed between seasons	72	30,25	166	69,75	0	0,00	31,0251	0,0001*	2,0030	0,8487	5386,5	,7354
		Average - Duration and timing of seasons	**47**	**19,75**	**191**	**80,25**	**0**	**0,00**	**23,0977**	**0,0016***	**0,5511**	**0,9901**	**5501,5**	**,9773**
Physical system														
FRESHWATER	Mean river flow	Change in mean river flow	12	5,04	226	94,96	0	0,00	13,4574	0,0617	14,8474	0,0110*	5057,5	,0104*
		Change high mountain springs flow	10	4,20	208	87,39	20	8,40	18,1992	0,0111*	4,2261	0,5173	5148,5	,1766
		Average - Mean river flow	**11**	**4,62**	**217**	**91,18**	**10**	**4,20**	**16,3390**	**0,0220***	**6,8599**	**0,2313**	**4950,5**	**,0537**
	River and lake floods	Change surface flooded by floods	73	30,67	109	45,80	56	23,53	65,5495	0,0000*	16,8785	0,0047*	4578,0	,0208*
		Change number of floods and overflows of rivers	62	26,05	121	50,84	55	23,11	55,7326	0,0000*	11,8848	0,0364*	4795,0	,0770
		Average - River and lake floods	**68**	**28,36**	**115**	**48,32**	**56**	**23,32**	**63,2240**	**0,0000***	**14,8373**	**0,0111***	**4648,5**	**,0374***
		Change duration of temporal rivers	24	10,08	214	89,92	0	0,00	15,6958	0,0280*	6,5482	0,2565	4959,5	,0237*

	Fresh water availability/quality	Change duration of irrigation water	20	8,40	214	89,92	4	1,68	4,6263	0,7055	7,3595	0,1952	5351,5	,5100
		Change duration of high mountain springs	15	6,30	202	84,87	21	8,82	20,0756	0,0054*	4,6444	0,4608	5099,5	,1556
		Average - Fresh water availability/quality	**20**	**8,26**	**210**	**88,24**	**8**	**3,50**	**8,6850**	**0,2760**	**3,0603**	**0,6907**	**5001,5**	**,1595**
	Water temperature of rivers and lakes	Change water temperature of rivers and lakes	162	68,07	72	30,25	4	1,68	10,3360	0,1703	3,1980	0,6695	5148,5	,3289
		Average - Water temperature of rivers and lakes	**162**	**68,07**	**72**	**30,25**	**4**	**1,68**	**10,3360**	**0,1703**	**3,1980**	**0,6695**	**5148,5**	**,3289**
	Lake level	Change duration of high mountain lakes	38	15,97	88	36,97	112	47,06	20,3741	0,0048*	1,9723	0,8530	5358,5	,6943
		Average - Lake level	**38**	**15,97**	**88**	**36,97**	**112**	**47,06**	**20,3741**	**0,0048***	**1,9723**	**0,8530**	**5358,5**	**,6943**
	Riverbank erosion and sedimentation	Change in rivers´ erosion grade	114	47,90	114	47,90	10	4,20	13,3446	0,0641	3,6464	0,6014	5253,5	,5230
		Average - Riverbank erosion and sedimentation	**114**	**47,90**	**114**	**47,90**	**10**	**4,20**	**13,3446**	**0,0641**	**3,6464**	**0,6014**	**5253,5**	**,5230**
SOIL & LAND	Soil erosion/ landslides	Change soil erosion	100	42,02	134	56,30	4	1,68	6,1630	0,5209	3,6861	0,5954	4980,5	,1863
		Change number of landslides	112	47,06	126	52,94	0	0,00	35,9058	0,0000*	1,6627	0,8936	5316,5	,6285
		Average - Soil erosion/ landslides	**106**	**44,54**	**130**	**54,62**	**2**	**0,84**	**17,6480**	**0,0140***	**1,9900**	**0,8505**	**5281,0**	**,5954**
	Soil moisture	Change soil humidity	22	9,24	216	90,76	0	0,00	10,1386	0,1809	3,7439	0,5868	5491,5	,9288
		Average - Soil moisture	**22**	**9,24**	**216**	**90,76**	**0**	**0,00**	**10,1386**	**0,1809**	**3,7439**	**0,5868**	**5491,5**	**,9288**
	Soil fertility, structure and biology	Change percentage of organic matter in the soil	125	52,52	105	44,12	8	3,36	26,6071	0,0004*	13,1292	0,0222*	4704,0	,0448*
		Average - Soil fertility, structure and biology	**125**	**52,52**	**105**	**44,12**	**8**	**3,36**	**26,6071**	**0,0004***	**13,1292**	**0,0222***	**4704,0**	**,0448***
ICE & SNOW	Snowfall and snow cover	Change amount of snowfall per year	2	0,84	236	99,16	0	0,00	5,8809	0,5537	2,8760	0,7191	5456,5	,4497
		Change frequency of snowfalls after winter	48	20,17	190	79,83	0	0,00	41,5131	0,0000*	12,7043	0,0263*	4525,5	,0024*
		Change duration of snowfields	5	2,10	232	97,48	1	0,42	4,7433	0,6913	5,3863	0,3706	5323,5	,1374
		Change snow cover extension	10	4,20	227	95,38	1	0,42	5,3879	0,6127	7,0467	0,2172	5502,0	,9509
		Change size of snowfields	26	10,92	209	87,82	3	1,26	12,0057	0,1004	3,4054	0,6378	5474,0	,8847
		Average - Snowfall and snow cover	**18**	**7,65**	**219**	**91,93**	**1**	**0,42**	**34,8670**	**0,0000***	**10,0400**	**0,0741**	**4619,5**	**,0165***
	Seasonal ice formation	Change presence of ice sheet on rivers and lakes	37	15,55	198	83,19	3	1,26	13,1739	0,0680	6,4293	0,2667	4868,5	,0338*
		Change Ice sheet thickness	14	5,88	221	92,86	3	1,26	7,1580	0,4130	10,5494	0,0611	4858,0	,0017*

		Average - Seasonal ice formation	**26**	**10,71**	**210**	**88,03**	**3**	**1,26**	**11,3520**	**0,1240**	**7,8775**	**0,1631**	**4697,5**	**,0100***
Biological system														
FRESHWATER WILD FAUNA	Freshwater Fish spp Abundance	Change abundance of Fish	5	2,10	140	58,82	93	39,08	59,6577	0,0000*	6,9095	0,2275	4553,5	,0164*
		Average - Freshwater Fish spp Abundance	**5**	**2,10**	**140**	**58,82**	**93**	**39,08**	**59,6577**	**0,0000***	**6,9095**	**0,2275**	**4553,5**	**,0164***
	Freshwater Fish spp Distribution and migration	Change altitudinal distribution of Fish	27	11,34	28	11,76	183	76,89	31,6772	0,0000*	9,7433	0,0828	4987,5	,0447*
		Average - Freshwater Fish spp Distribution and migration	**27**	**11,34**	**28**	**11,76**	**183**	**76,89**	**31,6772**	**0,0000***	**9,7433**	**0,0828**	**4987,5**	**,0447***
	Freshwater Fish spp Disease/ pest/ mortality	Change frequency of diseases/parasites in Fish	43	18,07	2	0,84	193	81,09	5,4678	0,6031	4,5824	0,4689	5449,5	,3951
		Change frequency of mutations/deformities in Fish	45	18,91	0	0,00	193	81,09	0,0000	1,0000	0,0000	1,0000	5512,5	1,0000
		Change size of Fish	18	7,56	30	12,61	190	79,83	51,0591	0,0000*	2,8958	0,7160	5386,5	,6400
		Average - Freshwater Fish spp Disease/ pest/ mortality	**35**	**14,85**	**11**	**4,48**	**192**	**80,67**	**50,8982**	**0,0000***	**2,9153**	**0,7130**	**5395,5**	**,6642**
	Freshwater Fish spp Phenology	Change reproduction dates of Fish	36	15,13	1	0,42	201	84,45	6,9333	0,4359	2,6061	0,7604	5481,0	,5485
		Average - Freshwater Fish spp Phenology	**36**	**15,13**	**1**	**0,42**	**201**	**84,45**	**6,9333**	**0,4359**	**2,6061**	**0,7604**	**5481,0**	**,5485**
TERRESTRIAL WILD FAUNA	Terrestrial Wild fauna Abundance	Change abundance Terrestrial animals (mammals, reptiles	9	3,78	228	95,80	1	0,42	11,0819	0,1351	7,4738	0,1877	5351,5	,3228
		Change abundance Birds	10	4,20	227	95,38	1	0,42	9,8269	0,1986	10,3742	0,0653	5203,5	,0874
		Change abundance Insects	34	14,29	204	85,71	0	0,00	11,0380	0,1370	2,1492	0,8281	5512,5	1,0000
		Change abundance Wild Hives	8	3,36	216	90,76	14	5,88	15,0140	0,0358*	4,8258	0,4375	5372,5	,5515
		Average - Terrestrial Wild fauna Abundance	**15**	**6,41**	**219**	**91,91**	**4**	**1,68**	**9,3493**	**0,2285**	**6,2425**	**0,2833**	**5109,5**	**,2418**
	Terrestrial Wild fauna composition (assemblage of species)	Change presence new Bird	56	23,53	179	75,21	3	1,26	6,5485	0,4773	4,0285	0,5453	5110,0	,2508
		Change presence new Insects	191	80,25	33	13,87	14	5,88	33,3459	0,0000*	5,2387	0,3874	5243,0	,3366
		Average - Terrestrial Wild fauna composition	**124**	**51,89**	**106**	**44,54**	**9**	**3,57**	**13,6719**	**0,0573**	**3,3810**	**0,6415**	**5362,5**	**,6965**
	Terrestrial Wild fauna Distribution and migration	Change altitudinal distribution Terrestrial animals	68	28,57	160	67,23	10	4,20	42,5654	0,0000*	2,4553	0,7832	5197,5	,4083
		Change altitudinal distribution Birds	203	85,29	31	13,03	4	1,68	38,0769	0,0000*	7,8184	0,1665	5250,0	,3366
		Change altitudinal distribution Insects	213	89,50	22	9,24	3	1,26	13,4623	0,0616	7,2349	0,2038	5372,5	,5515

		Average - Terrestrial Wild fauna Distribution and migration	**161**	**67,79**	**71**	**29,83**	**6**	**2,38**	**44,8488**	**0,0000***	**7,4719**	**0,1878**	**5354,5**	**,7044**
	Terrestrial Wild fauna Disease/ pest/ mortality	Change abundance of diseases/parasites in Terrestrial animals	50	21,01	184	77,31	4	1,68	13,1548	0,0684	9,8153	0,0806	4952,5	,0995
		Change frequency of mutations/deformities in Terrestrial animals	230	96,64	5	2,10	3	1,26	12,3099	0,0908	3,9033	0,5634	5474,0	,7408
		Change abundance of starving Terrestrial animals	134	56,30	99	41,60	5	2,10	27,1373	0,0003*	9,2643	0,0990	4655,0	,0321*
		Change abundance of diseases/parasites in Birds	227	95,38	7	2,94	4	1,68	14,4338	0,0440*	6,7070	0,2434	5257,0	,0624
		Change frequency of mutations/deformities in Birds	233	97,90	1	0,42	4	1,68	6,9333	0,4359	2,7778	0,7342	5425,0	,0956
		Change size of Birds	207	86,97	28	11,76	3	1,26	20,1350	0,0053*	6,8342	0,2333	5463,5	,8514
		Average - Terrestrial Wild fauna Disease/ pest/ mortality	**180**	**75,70**	**54**	**22,69**	**4**	**1,61**	**34,9853**	**0,0000***	**7,7262**	**0,1720**	**4746,0**	**,0842**
	Terrestrial Wild fauna Phenology	Change hibernation dates Terrestrial animals	112	47,06	121	50,84	5	2,10	14,4164	0,0443*	8,7656	0,1188	5271,0	,5517
		Change reproduction dates Terrestrial animals	170	71,43	60	25,21	8	3,36	7,4480	0,3838	11,4410	0,0433*	5169,5	,3304
		Change migration dates Birds	85	35,71	150	63,03	3	1,26	15,7593	0,0274*	0,9158	0,9691	5428,5	,8302
		Change reproduction dates Birds	178	74,79	56	23,53	4	1,68	4,7416	0,6915	0,6306	0,9866	5414,5	,7759
		Change activity periods Insects	62	26,05	176	73,95	0	0,00	8,6445	0,2792	2,6304	0,7567	5344,5	,6372
		Change migration dates Insects	2	0,84	2	0,84	234	98,32	6,0958	0,5286	3,7434	0,5869	5456,5	,4497
		Average - Terrestrial Wild fauna Phenology	**102**	**42,65**	**94**	**39,57**	**42**	**17,79**	**11,9027**	**0,1038**	**2,4035**	**0,7910**	**5303,5**	**,6487**
TERRESTRIAL WILD FLORA	Wild flora Abundance	Change abundance Riverside trees	36	15,13	202	84,87	0	0,00	11,2378	0,1286	2,2448	0,8143	5449,5	,8285
		Average - Wild flora Abundance	**36**	**15,13**	**202**	**84,87**	**0**	**0,00**	**11,2378**	**0,1286**	**2,2448**	**0,8143**	**5449,5**	**,8285**
	Wild flora Distribution (plants-shrubs-trees)	Change altitudinal distribution Wild plants	195	81,93	35	14,71	8	3,36	14,9330	0,0369*	7,3985	0,1926	5124,0	,1765
		Average - Wild flora Distribution	**195**	**81,93**	**35**	**14,71**	**8**	**3,36**	**14,9330**	**0,0369***	**7,3985**	**0,1926**	**5124,0**	**,1765**
	Wild flora Disease/ pest/ mortality (plants-shrubs-trees)	Change abundance of diseases/plagues Wild plants	41	17,23	195	81,93	2	0,84	10,6509	0,1546	3,9504	0,5566	5439,0	,8139
		Average - Wild flora Disease/ pest/ mortality	**41**	**17,23**	**195**	**81,93**	**2**	**0,84**	**10,6509**	**0,1546**	**3,9504**	**0,5566**	**5439,0**	**,8139**
		Change flowering dates Wild plants	84	35,29	153	64,29	1	0,42	11,0196	0,1378	2,7728	0,7350	5096,0	,2842

	Wild flora Phenology (plants-shrubs-trees)	Change germination dates NTFP*	110	46,22	126	52,94	2	0,84	21,0241	0,0037*	1,2993	0,9350	5435,5	,8493
		Average - Wild flora Phenology	**97**	**40,76**	**140**	**58,61**	**2**	**0,63**	**21,5669**	**0,0030***	**1,5095**	**0,9120**	**5334,0**	**,6830**
	Wild flora Productivity and Quality (plants-shrubs-trees)	Change growing patterns Wild plants	100	42,02	135	56,72	3	1,26	21,7914	0,0028*	3,9784	0,5525	4830,0	,0897
		Change abundance of NTFP*	56	23,53	182	76,47	0	0,00	5,7103	0,5740	8,6524	0,1238	5295,5	,5285
		Change quality of NTFP*	206	86,55	32	13,45	0	0,00	5,8861	0,5531	4,2366	0,5159	5211,5	,2770
		Average - Wild flora Productivity and Quality	**121**	**50,70**	**116**	**48,88**	**1**	**0,42**	**14,4649**	**0,0435***	**6,5381**	**0,2573**	**5365,0**	**,7348**
LAND DEGRADATION	Wildfires	Change number of Fires	120	50,42	118	49,58	0	0,00	62,6718	0,0000*	4,1471	0,5284	5421,5	,8226
		Average – Wildfires	**120**	**50,42**	**118**	**49,58**	**0**	**0,00**	**62,6718**	**0,0000***	**4,1471**	**0,5284**	**5421,5**	**,8226**
Human system														
CULTIVATES PLANT SPP	Cultivated spp productivity and quality	Change agricultural production	55	23,11	177	74,37	6	2,52	16,0966	0,0242*	7,9603	0,1584	5376,0	,7001
		Change growing patterns Crops	128	53,78	103	43,28	7	2,94	20,7014	0,0042*	8,6879	0,1222	5481,0	,9376
		Average - Cultivated spp productivity and quality	**92**	**38,45**	**140**	**58,82**	**7**	**2,73**	**26,6770**	**0,0004***	**11,1797**	**0,0479***	**5434,5**	**,8581**
	Cultivated spp disease/ pest/ mortality	Change abundance of plagues in Crops (insects/nematodes)	19	7,98	214	89,92	5	2,10	18,9171	0,0085*	2,6277	0,7571	5351,5	,5100
		Change abundance of diseases in Crops (viruses/bacteria)	22	9,24	211	88,66	5	2,10	23,4700	0,0014*	3,1910	0,6706	5376,0	,5959
		Change percentage of damaged/mortality in Crops	39	16,39	193	81,09	6	2,52	12,3169	0,0906	3,5346	0,6182	5502,0	,9736
		Average - Cultivated spp disease/ pest/ mortality	**27**	**11,20**	**206**	**86,55**	**5**	**2,24**	**16,1105**	**0,0241***	**3,6900**	**0,5949**	**5383,5**	**,7173**
	Cultivated spp Phenology and reproduction	Change germination/flowering/maturation dates Crops	56	23,53	176	73,95	6	2,52	8,6571	0,2782	1,9976	0,8495	5344,5	,6372
		Change altitudinal distribution Crops	107	44,96	126	52,94	5	2,10	72,6342	0,0000*	2,1906	0,8222	5197,5	,4368
		Average - Cultivated spp Phenology and reproduction	**82**	**34,24**	**151**	**63,45**	**6**	**2,31**	**38,3777**	**0,0000***	**1,7889**	**0,8775**	**5130,5**	**,3735**
PASTURES AND GRASSLAND	Pasture availability and productivity	Change Pasture availability throughout the year	5	2,10	109	45,80	124	52,10	10,5163	0,1612	114,1420	0,0000*	3983,0	,0002*
		Change amount of extra feed in barn for Livestock	5	2,10	111	46,64	122	51,26	23,2248	0,0016*	110,5463	0,0000*	3801,0	,0000*
		Average - Pasture availability and productivity	**5**	**2,10**	**110**	**46,22**	**123**	**51,68**	**17,1771**	**0,0163***	**118,9435**	**0,0000***	**3793,5**	**,0000***
		Change Pasture quality	51	21,43	62	26,05	125	52,52	9,7128	0,2054	72,1059	0,0000*	4630,5	,0133*

	Pasture spp composition, distribution and quality	***Average - Pasture spp composition, distribution and quality***	**51**	**21,43**	**62**	**26,05**	**125**	**52,52**	**9,7128**	**0,2054**	**72,1059**	**0,0000***	**4630,5**	**,0133***
LIVESTOCK	Livestock productivity and quality	Change production by Livestock head	31	13,03	80	33,61	127	53,36	8,6890	0,2758	78,1098	0,0000*	4301,5	,0016*
		Change quality raw material of Livestock	79	33,19	32	13,45	127	53,36	11,8371	0,1060	18,9236	0,0020*	5456,5	,8397
		Change honey production by Hive	9	3,78	28	11,76	201	84,45	7,3325	0,3951	149,0778	0,0000*	5106,5	,1205
		Average - Livestock productivity and quality	**40**	**16,67**	**47**	**19,61**	**152**	**63,73**	**6,9140**	**0,4379**	**71,1905**	**0,0000***	**4087,5**	**,0007***
	Livestock disease/ pest/ mortality	Change abundance of diseases/abortions/dehydration in Livestock	18	7,56	93	39,08	127	53,36	9,3752	0,2268	67,3208	0,0000*	4249,0	,0014*
		Change abundance of diseases/parasites/predators in Bees	1	0,42	38	15,97	199	83,61	8,1311	0,3212	174,1347	0,0000*	4910,5	,0429*
		Change percentage of death Bees per Hive	6	2,52	29	12,18	203	85,29	7,5792	0,3712	171,3836	0,0000*	4956,0	,0361*
		Change frequency of mutations/deformities in Bees	13	5,46	21	8,82	204	85,71	10,5889	0,1576	153,1498	0,0000*	4851,0	,0041*
		Average - Livestock disease/ pest/ mortality	**10**	**3,99**	**45**	**19,01**	**183**	**77,00**	**5,2122**	**0,6341**	**112,6890**	**0,0000***	**3568,0**	**,0000***
	Livestock phenology	Change unusual behaviour in Livestock	83	34,87	27	11,34	128	53,78	2,0764	0,9555	44,6362	0,0000*	5138,0	,1457
		Change altitudinal distribution of livestock	68	28,57	34	14,29	136	57,14	9,9369	0,1922	36,4035	0,0000*	5155,5	,2088
		Change Swarm grouping and Bee breeding dates	15	6,30	19	7,98	204	85,71	4,7109	0,6952	121,3343	0,0000*	5033,0	,0293*
		Average - Livestock phenology	**55**	**23,25**	**27**	**11,20**	**156**	**65,55**	**1,9210**	**0,9641**	**57,3497**	**0,0000***	**4480,5**	**,0045***

*NTFP: Non timber forest products

Table 3.4. SM2. Robustness Analysis: Results of Poisson regression showing sociodemographic correlations of LICCI Indices

	LICCI INDEX CORE MODEL	LICCI INDEX Excluded Women	LICCI INDEX Cluster Zones	LICCI INDEX Age Range	LICCI INDEX Formal schooling	LICCI INDEX Linear Model
Profession (*farmers* omitted category)						
Shepherds	0.0862***	0.0728**	0.0862***	0.0934***	0.0951***	4.6754**
	(0.0297)	(0.0307)	(0.0321)	(0.0294)	(0.0294)	(2.1246)
Ranchers	0.0618	0.0604	0.0618**	0.0565	0.0676	3.3239
	(0.0430)	(0.0434)	(0.0262)	(0.0429)	(0.0429)	(3.1118)
Beekeepers	0.0347	0.0228	0.0347	0.0333	0.0328	1.8678
	(0.0329)	(0.0350)	(0.0420)	(0.0330)	(0.0326)	(2.3364)
Agricultural ranchers	0.0766**	0.0821**	0.0766***	0.0740**	0.0889***	4.1289
	(0.0338)	(0.0347)	(0.0259)	(0.0338)	(0.0332)	(2.4320)
Other professions	-0.0163	-0.0086	-0.0163	-0.0161	-0.0209	-0.6558
	(0.0267)	(0.0279)	(0.0338)	(0.0270)	(0.0266)	(1.8517)
Age	0.0223***	0.0224***	0.0223***		0.0246***	1.1083**
	(0.0064)	(0.0065)	(0.0085)		(0.0063)	(0.4333)
Age^2	-0.0002***	-0.0002***	-0.0002***		-0.0002***	-0.0092**
	(0.0001)	(0.0001)	(0.0001)		(0.0001)	(0.0036)
Female	-0.0242		-0.0242	-0.0221	-0.0244	-1.2985
	(0.0382)		(0.0673)	(0.0383)	(0.0380)	(2.7047)
School level (*no formal studies* omitted category						
Primary school	-0.0068	-0.0159	-0.0068	-0.0056		-0.2614
	(0.0275)	(0.0286)	(0.0241)	(0.0282)		(1.9642)
Secondary and vocational studies	-0.0288	-0.0328	-0.0288	-0.0248		-1.4787
	(0.0339)	(0.0351)	(0.0444)	(0.0336)		(2.4106)
Bachelor, Master and PhD	-0.0960**	-0.1134**	-0.0960	-0.0912**		-4.7061
	(0.0436)	(0.0453)	(0.0556)	(0.0438)		(3.0080)
Parents born in Sierra Nevada	-0.1095**	-0.1000	-0.1095**	-0.0951	-0.0894	-5.4219
	(0.0514)	(0.0520)	(0.0487)	(0.0514)	(0.0506)	(3.4894)
Grandparents born in Sierra Nevada	0.0533**	0.0541**	0.0533***	0.0467	0.0493**	2.6477
	(0.0246)	(0.0250)	(0.0167)	(0.0247)	(0.0245)	(1.6565)
Years of experience	-0.0016	-0.0016	-0.0016**	-0.0020**	-0.0014	-0.0804
	(0.0011)	(0.0012)	(0.0007)	(0.0010)	(0.0011)	(0.0760)
Number of activities in nature	0.0422***	0.0375***	0.0422***	0.0426***	0.0418***	2.2094***
	(0.0099)	(0.0101)	(0.0124)	(0.0099)	(0.0099)	(0.7048)
Zone Granada´s surroundings	0.0745**	0.0814**	0.0745***	0.0835**	0.0768**	3.7004
	(0.0377)	(0.0408)	(0.0162)	(0.0375)	(0.0374)	(2.6434)
Zone Lanjarón and Lecrín Valley	0.0007	0.0046	0.0007	0.0078	-0.0111	-0.0810
	(0.0406)	(0.0426)	(0.0121)	(0.0401)	(0.0401)	(2.8000)
Zone Poqueira Ravine	0.0483	0.0596	0.0483**	0.0486	0.0569	2.3232
	(0.0390)	(0.0413)	(0.0198)	(0.0390)	(0.0386)	(2.7105)
Zone Trevélez and Bérchules Ravines	0.0979**	0.1309***	0.0979***	0.1099***	0.1028***	5.0629
	(0.0385)	(0.0410)	(0.0117)	(0.0379)	(0.0381)	(2.7082)
Zone Ohanes Ravine	0.1038***	0.1111***	0.1038***	0.1182***	0.1085***	5.4288
	(0.0389)	(0.0423)	(0.0168)	(0.0385)	(0.0388)	(2.7555)
Zone Nacimiento Valley	0.0421	0.0517	0.0421***	0.0566	0.0453	1.9807
	(0.0397)	(0.0416)	(0.0161)	(0.0391)	(0.0396)	(2.7635)
Zone La Calahorra Valley	0.0116	0.0263	0.0116	0.0252	0.0047	0.4012
	(0.0391)	(0.0410)	(0.0102)	(0.0388)	(0.0387)	(2.6960)
Age range (25-39 omitted category)				.		
Age range (40-54)				0.1485***		
				(0.0473)		
Age range (55-69)				0.1511***		
				(0.0516)		
Age range (70-84)				0.1217**		
				(0.0613)		
Age range (85 and over)				0.1651		
				(0.1088)		
Formal schooling					-0.0136	
					(0.0271)	
_cons	3.1822***	3.1755***	3.1822***	3.6896***	3.0673***	13.3663
	(0.1971)	(0.1998)	(0.2640)	(0.0864)	(0.1898)	(13.4212)
N	238	222	238	238	238	238

Chapter IV

Environmental changes driven by climate change and other drivers of change. A social network analysis of local perceptions in Sierra Nevada, Spain

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Abstract

Climate change manifests differently around the world, with the geographical location and the biophysical characteristics of a region shaping the impacts felt in a region. Moreover, local climate change impacts might be amplified through interactions with other drivers of change acting locally. Indigenous people and local communities with detailed knowledge of the environment can differentiate with precision and detail environmental changes occurring in their social-ecological systems as well as the drivers of the observed impacts. In this work, we draw on this source of knowledge to study interactions between environmental changes driven by climate change and other drivers of change as perceived by local communities of Sierra Nevada, a mountainous area of Spain. We used a survey instrument (n=238 respondents) to identify the most impactful changes in the climatic, physical, biological, and human systems, and their perceived driver of change. We used social network analysis 1) to identify interactions among changes attributed to climate and other drivers of change; and 2) to analyze cascading effects generated by climate change impacts. Results showed how ILK of respondents influenced the number and kind of interactions among environmental changes perceived on their social-ecological systems of Sierra Nevada. Respondents perceived climate change as the main driver of change in the region, and highlighted elements of the human system as the most impacted, although they also showed great concern about impacts on the hydric resources. Several of the changes identified are driven by the cascading effects of changes in the climatic system, but also by the compounding effects of these changes and other drivers of change. Beyond adding to the growing number of works pointing at the importance of local knowledge systems, our findings suggest ways to include local knowledge in the co-management of the territory and in local adaptation policies.

Key words: Global change; Indigenous and local knowledge; mountains; cascading effects, network analysis of environmental changes.

1. Introduction

While climate change affects all ecosystems on Earth, some areas are more affected than others, with some hot-spots where climate change has more visible manifestations (Dilley 2006; Ackerly et al. 2010; Fraser et al. 2013; de Sherbinin 2014). Coastal areas and islands, tropical regions, polar latitudes, and mountain ranges are among the areas already experiencing large climate change impacts (Hock et al. 2019; Magnan et al. 2019; Meredith et al. 2019; Oppenheimer et al. 2019). In these areas, changes in the climatic system disproportionally affect elements of the physical, the biological and the human systems. Moreover, interactions between changes in different components of these systems further amplify change through cascading or interaction effects (IPCC & IPBES 2020).

Cascading effects across system's components is a well-known phenomenon in ecology and ecosystem services studies (Knowlton & Jackson 2008; Brook et al. 2008; Wookey et al. 2009), as well as in resilience and sustainability frameworks (Folke et al. 2004; Xu et al. 2009; Weatherhead et al. 2010). For example, precipitation decrease generates impacts on soil humidity (Seneviratne et al. 2010), which in turn affects the growing rate of wild plants (Wratt et al. 2006; Inouye & Wielgolaski 2013). At the same time, the reduction of plant biomass impacts wild fauna, through the reduction of the abundance and quality of pastures (Florenzano 2004; He & Richards 2015). Similarly, changes in mean temperature also result in floral phenological changes affecting flowering or fruiting periods, with potential consequences on human livelihoods (Cook et al. 2012; Mayor et al. 2017).

Moreover, Climate change impacts are often aggravated by interactions with other anthropogenic direct and indirect drivers of environmental change (Rockström et al. 2009; Steffen et al. 2015). Thus, land use change (Foley et al. 2011), pollution (Crippa et al. 2020), population growth (O'Neill et al. 2010), population displacement (Minx et al. 2011), or political decisions (Helm 2010) accentuate climate change impacts in elements of the climatic, physical, biological and/or human systems. For example, changes in the availability of freshwater in a region can result from rainfall decrease events and temperature increase, but the impacts of changes in freshwater availability can be aggravated by the increase of water consumption resulting from changes in the intensity of agricultural activities in a region (Peñuelas et al. 2013; Scheffers et al. 2016; Arneth et al. 2020).

While scientific understanding of global climate change impacts has improved enormously during the last decades (Getz et al. 2018; Bonan & Doney 2018), regional models are less precise. This is so, partially due to the lack of relevant long data series of climatic and biophysical components and data on interactions between climate change and other drivers of change (Stott et al. 2010; Rosenzweig & Neofotis 2013; Lucas-Picher et al. 2013). Regional models are particularly imprecise in isolated or data-deficient regions, where researchers largely rely on downscaling techniques (Fernández-Llamazares et al. 2017).

Researchers and members of the Intergovernmental Panel on Climate Change (IPCC) have advocated for the importance and consideration of Indigenous and Local Knowledge (ILK) as an alternative, but equally valid, source of knowledge to understand climate change impacts at the local level (Barnes et al. 2013; Baul & McDonald 2015; Chanza & De Wit 2016; Ford et al. 2016; Maldonado et al. 2016; Altieri & Nicholls 2017; Reyes-García et al. 2019). Indigenous people and local communities (IPLC) have developed a deep understanding of the ecological relations in the ecosystems that sustain them. This understanding is the foundation of their knowledge system, which is at the basis of formal and informal norms and rules to manage nature (Armitage 2008; Ostrom 2009; Bodin et al. 2014; Berkes 2017). This knowledge also allows IPLC to detect changes in components of the elements of their social-ecological systems (Mclean 2010; Smith & Sharp 2012; Cramer et al. 2014; Ford et al. 2016; Reyes-García et al. 2019; Hu et al. 2020). Indeed, previous research shows that IPLC can detect changes in different components of the climatic system, such as extreme temperatures or the frequency and length of hot or cold waves

(Manandhar & Schmidt 2011; Boissière et al. 2013; Joshi et al. 2013; Plummer et al. 2014). IPLC can also detect changes in temporal and spatial rainfall distribution (Boillat & Berkes 2013; Gurgiser et al. 2016), changes in the duration of rainfall events (Fassnacht et al. 2018), or changes in the predictability of rainfalls (Leonard et al. 2013; Sowman & Raemaekers 2018). Moreover, the holistic nature of ILK also allows IPLC to perceive the multiple connections among the climatic, physical, biological, and human components of their social-ecological system, thus being a potential source of knowledge to identify impacts that might threaten the functioning and structure of the system and their overall resilience (Folke 2006; Green & Raygorodetsky 2010; Berkes 2017; Ingty 2017). Despite the potential of ILK, few studies have systematically analysed the network of connections among the different environmental impacts perceived by IPLC and between the impacts and their drivers.

To address this gap, in this study we assess how local communities in Sierra Nevada, a mountain region of Spain, perceive environmental changes and the drivers of such changes. Specifically, we assess the most impactful changes on the social-ecological system perceived by our informants and the network of drivers of such impacts. Given that ILK is patterned by sociodemographic characteristics of informants (Reyes-García et al. 2009; Berkes 2012; Benyei et al. 2020; García-del-Amo et al. 2021), we compare perceptions of climate change impacts reported by people devoted to agropastoral activities with perceptions reported by local inhabitants not fully devoted to the primary sector. We explore our data using social network analysis (SNA). SNA has been broadly applied to study resilience and the structure of social-ecological systems (Newman & Dale 2005; Bodin et al. 2006; Bodin & Tengö 2012), the transmission and exchange of ILK among knowledge holders (Calvet-Mir & Salpeteur 2016; Díaz-Reviriego et al. 2016), and natural resources co-management (Bodin et al. 2006; Calvet-Mir et al. 2015; Salpeteur et al. 2017). SNA has also been used for the analysis of simultaneous effect of multiple drivers of change and its repercussions on regimen shifts of ecosystems (Rocha et al. 2015). However, the technique has not yet been used to study perceptions of IPLC regarding environmental change and its drivers.

2. Methodology

2.1. Study region

Given the recognized importance of mountain regions in climate change and global change studies (Kohler et al. 2010; Gurung et al. 2012; Messerli 2012; Zamora et al. 2017; Rogora et al. 2018), we conducted our study in Sierra Nevada, the highest mountain region in the southeast of the Iberian Peninsula, with more than 25 peaks over 3000 m.a.s.l. Sierra Nevada is located in a semi-arid region, although it displays a cold climate with cold and dry summers, presenting large thermal variations (Gómez-Zotano et al. 2015). Due to its Mediterranean climate, rainfall is not very abundant, with most precipitations concentrated in winter and spring. Precipitations in the mid-high areas of the mountain are more abundant than in the low areas. Sierra Nevada is also characterized by the presence of snow, with several snowfields and permafrost areas on the summits, which used to remain during the summer and which have given name to the mountain range that translates as "snowed mountain" (Oliva et al. 2018). The biophysical characteristics of the mountain range have allowed the permanence of some relict species from the glacial period (Blanca et al. 2001; Médail & Diadema 2009) and the existence of great variety of ecological conditions and biodiversity with many endemic species (Martín-García et al. 2004; Oliva et al. 2014).

Sierra Nevada is, indeed, one of the most important biodiversity hot-spots of Europe and the Mediterranean basin (Blanca et al. 1998, 2001; Cañadas et al. 2014; Pérez-Luque et al. 2015). Most of the region belongs to a Natural park (1989), a National park (1999), and/or a Biosphere Reserve (1986), the last recognizing the importance of traditional ecosystem management in biodiversity maintenance. Indeed, since the Islamic period (8th century), local inhabitants have transformed the territory through the construction of a sophisticated water management system that consists of a network of water ditches dug on the ground (acequias), which collect melting water from the summits and canalize it along the slopes to the villages and agricultural fields. Such channels are combined with galleries dug into the slopes in the lower areas of the mountain (*qanats* or *cimbras*) for the extraction of underground water from the summits (Pulido-Bosch & Sbih 1995; Roldán & Moreno 2010; Jódar et al. 2017; Ruiz-Ruiz & Martín-Civantos 2017; Martos-Rosillo et al. 2019). This water management system increases water infiltration, recharging the aquifers and increasing the availability of water during the dry summer months. The system also allows to extend the surface and duration of high-mountain meadows during the summer, favors the existence of flora species with higher water requirements, and makes possible agriculture in a slope area (Ruiz-Ruiz & Martín-Civantos 2017; Martos-Rosillo et al. 2019). The canalization and redistribution of melting water also reduces erosion due to runoff water (Pulido-Bosch & Sbih 1995; Escalante Fernández & García Rodríguez, Manuel Fermín Villarroya 2006; Jódar et al. 2017) and favors the production of highland pastures and increased lowland agrobiodiversity. Communities sharing irrigation sources have created water management rules to ensure water equitable distribution and use. Such rules take into account both biophysical (i.e., the evapotranspiration of the water at different times of the year) and social factors (i.e., order and weekly need of water of each member), being a clear example of common pool resources management (Ostrom 1990). This complex water-management system, part of the local knowledge system, has been orally transmitted for more than 13 centuries allowing the coevolution of communities and natural elements of ecosystems and the formation of a unique social-ecological system (Blondel 2006; Plieninger et al. 2006; Valladares 2007; Iniesta-Arandia et al. 2014).

Nowadays, Sierra Nevada social-ecological system is seriously threatened by multiple drivers of change. As many other rural areas in Europe, during the second half of the 20th century, the population of Sierra Nevada shirked due to rural exodus. The configuration of agricultural areas, in small plots and on steep slopes, prevented agriculture modernization. Because agriculture was not economically profitable, many people migrated (Prados Velasco & Valle Ramos 2010). In 1956, agriculture occupied 17.8% of the current protected area surface versus the 4.7% of the protected area surface occupied nowadays (Zamora 2016). There has also been a decrease of the number of shepherds and ranchers and of pasture surface, mainly in high mountain areas (Rodriguez Martínez 2001). At the same time, reforestation campaigns, aiming to reduce soil erosion, resulted in a land use change in more than 40% of the region. Finally, the establishment of protected areas reduced the territory managed by local communities *(Gutiérrez-Hernández et al. 2016; Zamora et al. 2016)*. In addition to social changes, during the last decades, climate change has also affected the region in many ways. Rainfall reduction and increase of mean temperatures are reducing drastically hydric resources in the region, extending the duration of drought periods (Ruiz Sinoga et al. 2011; Oliva et al. 2014; Zamora et al. 2017). Snowfields no longer last all summer and permafrost areas have disappeared (Gómez-Ortiz et al. 2015; Oliva et al. 2018) and several springs and wells dried several years ago. All these changes further impact high mountain meadows, the abundance and distribution of species, and phenological cycles, but they also threat the continuity of traditional livelihoods, including livelihoods based on agriculture, pastoralism and beekeeping (Zamora et al. 2016).

2.2. Data collection and coding

From June to December 2018, we conducted 238 surveys in 33 villages of Sierra Nevada. We applied a convenience stratified sampling (Shively 2011) to select villages with more than 300 inhabitants around the mountainous region. To ensure that participants had lived in the area to perceive environmental changes, we only interviewed people who had lived in the region more than 25 years. We stratified participants in two groups: the *expert* group (n=175) included people directly involved in agropastoral activities: farmers, shepherds, ranchers, beekeepers, and agricultural ranchers (farmers who also have livestock) and the *non-expert* group (n=63) included people who only conduct these activities as a complement or for leisure.

All participants responded to a survey that had three sections. In the first section, we collected basic sociodemographic characteristics of informants, including age and profession (SM, Table 4.7). In the second section, we presented participants with a list of 95 environmental changes potentially occurring in the area and asked them to identify the five changes with largest negative impact on their agropastoral activities and describe the impacts. The list of environmental changes was constructed based on literature review and local knowledge. Since our aim was to identify changes driven by climate change and potential synergies with other drivers of change, we reviewed both the literature on climate change impacts on the study region and the literature on local observations of change attributed to climate change. We classified information of changes reported in the literature considering whether the change was observed on elements of the climatic, the physical, the biological, or the human system, further differentiating between subsystems, impacted elements, and finally changes (Reyes-García et al. 2019). We then conducted 30 in-depth semi-structured interviews with elderly people, locally recognized as knowledgeable, to assess which of all the changes reported in the literature had actually been observed in the study area. The combination of these sources of information resulted in the list of 95 changes that were locally perceived and –at least partially- attributed to climate change and that was the basis of our survey (See SM Table 4.6).

In the third section of the survey, we asked informants about the perceived drivers of these changes. Although all elements in our list are –at least partially- driven by climate change, they could also be affected by other drivers of change. So, for each of the five environmental changes reported as most impactful, informants were also asked to identify the two main drivers. To minimize biases, we did not use the term climate change in the survey but referred to environmental change.

Description of the impacts and drivers of environmental changes were noted verbatim and later coded. Coding focused on relational aspects. When asked to describe impacts, informants often reported relations between different components of the system (i.e., cascading effects). For example, one responded selected "changes in the amount of rainfall" as one of the changes most impacting his activity, further arguing that "*Changes in amount of rainfall affect me the most because it reduces rivers flow. This decreases the availability of irrigation water, which reduces orchard production*". In that case, we classified *Changes in amount of rainfall* as the primary change and then *Changes in river flow* and *Changes in cultivated crop production* as cascading effects. To code cascading effects, we use the same list of environmental changes described above. After analysing responses, we found six new changes, driven by cascading effects that were not included in the original list of environmental changes, for which our final list has 101 environmental changes.

Drivers were classified based on the categories of direct and indirect drivers of change proposed by IPBES (Díaz et al. 2019) (Table 4.1). Based on survey responses, we adapted the list including only the categories mentioned by respondents and including an additional one, as some people attributed the observed environmental changes to Earth's natural cycles. However, the Earth natural cycles was not included in further analysis, due to respondents did not consider it as a driver, but a normal environmental characteristic of the region.

Table 4.1. Drivers of environmental change. Adapted from Díaz et al. (2019).

Type of driver	***Name***	***Explanation***
Direct	Climate change	Environmental changes generated by variations of climatic conditions.

	Invasive Alien Species	Environmental changes generated by invasive animal and plant species coming from other parts of the world.
	Land use change	Environmental changes generated by the abandonment of crop fields and the associated loss of biodiversity in these areas.
	Pollution	Environmental changes generated by the excessive use of pesticides and herbicides.
	Resource extraction	Environmental changes generated by resource extraction, from water for irrigation and human consumption to honey by beekeepers.
Indirect	Governance of State – *Conservation policies*	Environmental changes generated by the application of policies that regulate ownership, use, and access to natural resources.
	Demographic – *Population dynamics*	Environmental changes generated by population movements including rural exodus to the cities and the return of neo-rural people.
	Technological – *Changes in technology used in the primary sector*	Environmental changes generated by changes in the primary sector like waterproofing of *acequias*, introduction of new crops' varieties and drip irrigation techniques, and presence of light-aircrafts dissolving clouds and reducing rainfall events.
	Governance – *Market interactions*	Environmental changes generated by economic pressures and the application of international standards created by markets.
Earth's natural cycles		Environmental changes generated by Earth´s natural cycles. This was not considered as a driver by local inhabitant but a normal cyclical environmental characteristic of the region.

2.3. Data analysis

We first conducted a descriptive analysis to determine which environmental changes were considered as most impactful by the local population and the perceived drivers of these changes. We also ran a non-parametric Kruskal-Wallis test between the type of driver and the system where changes were perceived to determine whether there were statistically significant relations between these variables.

We then used SNA to analyze the relations between impactful environmental changes driven by climate change and 1) their cascading effects (climate change network (CCN)), and 2) their drivers (global change network (GCN)). The CCN was developed with a one-mode adjacency matrix (square) in which rows and columns are the list of environmental changes driven by climate change (101x101). The GCN was created with a two-mode matrix, with the nine drivers of change identified as rows and the list of environmental changes as columns (9x101). Environmental changes and drivers of change represent the nodes of the networks. Cells in CCN matrices contained the number of respondents mentioning a relation between environmental changes, while cells in GCN contained the number of respondents mentioning a relation between environmental changes and drivers of change. A node is considered "active" if at least one of its cells of the matrix is different than 0. Numbers in cells represent the ties between nodes of the networks We used these numbers to represent the existence of relation (with thickness representing the number of respondents mentioning a relation). Ties also indicated the direction of the relation. Thus, in the CCN a tie indicated that an environmental change has a cascading effect generating another change, and in the GCN a tie indicated that a driver was listed as responsible for an environmental change. Due to the high number of interactions, in our graphical representation we include only ties with a strength equal or higher than two. The thickness of the ties was rescaled to a score from 1 to 3 for visualization.

For each network we calculated four different measures. First, we calculated network density, or the number of ties in the network expressed as a proportion of the maximum possible number of ties, where "1" represents a fully connected network (Borgatti et al. 2018). Second, we also calculated three network centralization measures, i.e., network indegree, network outdegree and network betweenness. Network centralization degrees (i.e., indegree and outdegree) of valued matrices considers the sums of the values of the ties of each node to give the overall network centralization measure. These measures basically quantify how dispersed are the centralities of the nodes, with higher scores meaning that a few central nodes generate most of the connections, by receiving (network indegree) or emitting (network outdegree) ties to the rest of the nodes located in the network periphery. Network betweenness quantifies the grade of modularity of the network, i.e., how much each small group (or module) contributes to minimize the distance between modules in the network. Network betweenness scores of GCNs were not possible to calculate with the two-mode matrices.

To analyze nodes' interactions, we calculated three centrality measures for each node: outdegree, indegree and betweenness scores. The o*utdegree* score of a node represents the number of outcoming ties sent by a node; for example, the number of cascading changes generated by an impactful environmental change. The *indegree* score of a node represents the number of incoming ties received by a node, for example the number of environmental changes attributed to a driver. Finally, the *betweenness* score of a node represents its degree of intermediation, or the proportion of all the shortest paths between two nodes of a network that pass through the node analyzed (Borgatti et al. 2018). Nodes with high betweenness scores filter interactions between other nodes, thus contributing to maintain the structure of the network.

We conducted separate analysis for experts and non-experts. As the sample size of the groups was different, we normalized results to be able to compare both networks. We compared CCNs and GCNs of both groups of participants analysing densities, network centralization measures and centrality degree scores of their nodes. All statistical analyses were conducted with SPSS version 22 and UCINET version 6.721 (Borgatti et al. 2002). Network diagrams were carried out with NetDraw version 2.168 (Borgatti 2002).

3. Results

3.1. Impactful environmental changes and their drivers

Out of the 101 environmental changes in our final list, respondents marked 77 (76.2%) as highly impactful for their livelihood activities (Supplementary material Table 4.6). We found differences between experts and non-experts on the perception of environmental changes. The group of experts mainly perceived changes in elements of the human system (40.1%), followed by changes in elements of the climatic (28.9%) and the physical systems (17.4%). The lowest number of changes referred to elements of the biological system (13.5%). Non-experts equally perceived changes across elements of the human (34%) and the climatic system (31.4%). As experts, non-experts also reported more impactful environmental changes refereeing to elements of the physical (22.1%) than to elements of the biological system (12.9%).

Respondents could attribute up to two drivers to each of the five environmental changes signalled as most impactful (238 respondents*5 environmental changes *2 drivers= 2380 ties). Some informants were not able to identify drivers for the impactful environmental changes reported and a few (15) reported Earth´s natural cycles as the reason of some perceived changes. Consequently, the number of ties was lower than the expecting, reaching 1358 ties. Experts cited 1014 relations and non-experts 344, which represent 57.94% and 54.6% of all possible relations that could be cited by each group (Table 4.2). The percentage of environmental changes attributed to each driver was similar between the two groups. Experts and non-experts attributed changes in elements of the climatic system to climate change, except some respondents who also mentioned the influence of light aircrafts in the region in changing rainfall patterns (Figure 4.1). Experts and non-experts also attributed changes on elements of the physical system to climate change, although they also referred to indirect drivers of change, and particularly to resource extraction, conservation policies, population dynamics or technological changes in primary sectors. For experts and non-experts, changes in elements of the biological system were mostly driven by conservation policies, although some also listed climate change, land use change, and pollution as drivers of change on elements of the biological system. Finally, respondents perceived that elements of the human system were impacted indistinctly by direct and indirect drivers of change. Indeed 50% of the most impactful environmental changes in elements of the human system listed were attributed to indirect drivers of change (Figure 4.1; Table 4.2).

The analysis of the distribution of the type of drivers and the system where changes were perceived showed that there were statistically significant differences in the distribution both for experts (X^2 =258.108; p=0.000) and non-experts (X^2 =99.694; p=0.000). In both groups, climate change was perceived as the main driver of the environmental changes in the list, representing 62% of experts' and 66.6% of non-experts´ responses. Climate change was identified as the main driver of change observed in elements of the climatic system (27.2% of experts and 29.6% of non-experts' responses), but also in elements of the physical and human systems (Figure 4.1; Table 4. 2). In relation to experts, non-experts attributed to climate change a higher percentage of observations of change in elements of the physical system (18.9% of non-experts and 15% of experts' responses). On the contrary, experts attributed to climate change a higher percentage of observations of change in elements of the human system than non-experts (17.4% of experts and 13.9% of non-experts' responses). Climate change was only attributed to 2.5% of experts' and 4.1% of non-experts' observations of change on elements of the biological system. Apart from climate change, pollution from pesticides (4.4% of experts' and 2.6% of non-experts' responses) and land use change (3.5% of experts' and 5.8% of non-experts' responses) were also perceived as relevant direct drivers of environmental change. Among the indirect drivers of change listed, both groups of respondents listed most frequently conservation policies (16.7% of experts' and 10.4% of non-experts' responses).

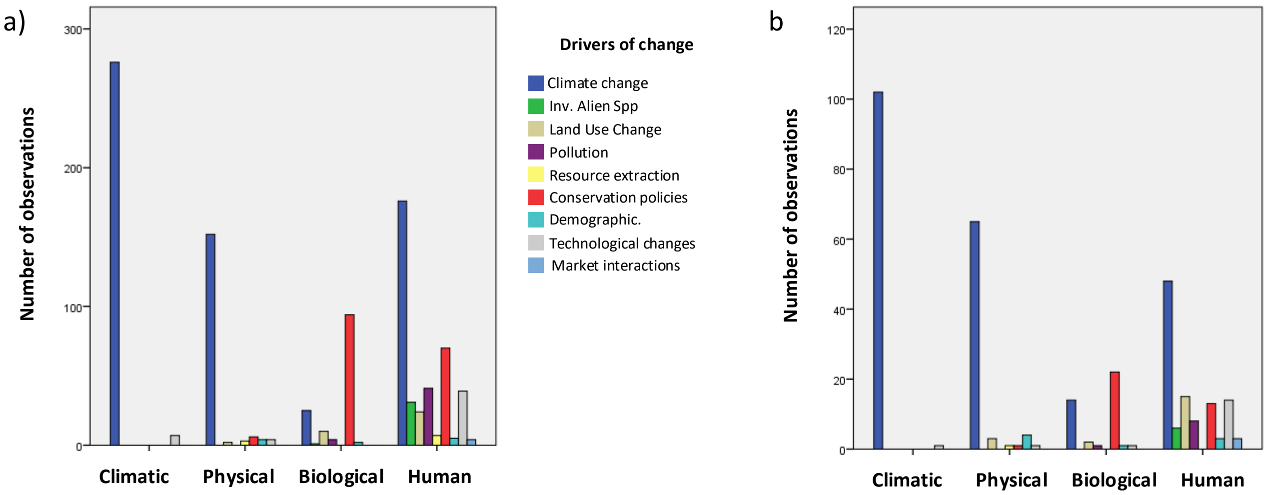

Figure 4.1. Number of the most impactful environmental changes observed on elements of the climatic, the physical, the biological, and the human system and attributed to different drivers of change by a) experts and b) non-experts.

Table 4.2. Frequency and percentage of environmental changes perceived by a) experts and b) non-experts on elements of the climatic, physical, biological and human systems and attributed to different drivers of change. **Total[1]** represents the frequency and the percentage of environmental changes attributed to each driver on all systems. **Total[2]** represents the frequency and the percentage of environmental changes on each system generated by all drivers.

Group		a) Experts (n=1014)					b) Non-experts (n=344)				
	Driver \ System	Climatic	Physical	Biological	Human	**Total[1]**	Climatic	Physical	Biological	Human	**Total[1]**
Direct drivers	*Climate change*	276 (27.22%)	152 (14.99%)	25 (2.46%)	176 (17.36%)	**629 (62.03%)**	102 (29.65%)	65 (18.89%)	14 (4.07%)	48 (13.95%)	**229 (66.57%)**
	Invasive alien species	-	-	1 (0.09%)	31 (3.06%)	**32 (3.15%)**	-	-	-	6 (1.74%)	**6 (1.74%)**
	Land use change	-	2 (0.20%)	10 (0.99%)	24 (2.37%)	**36 (3.55%)**	-	3 (0.87%)	2 (0.58%)	15 (4.36%)	**20 (5.81%)**
	Pollution	-	-	4 (0.39%)	41 (4.04%)	**45 (4.44%)**	-		1 (0.29%)	8 (2.32%)	**9 (2.62%)**
	Resource extraction	-	3 (0.29%)	-	7 (0.69%)	**10 (0.99%)**	-	1 (0.29%)	-	-	**1 (0.29%)**
Indirect Drivers	*Conservation-policies*	-	6 (0.59%)	94 (9.27%)	70 (6.90%)	**170 (16.76%)**	-	1 (0.29%)	22 (6.39%)	13 (3.78%)	**36 (10.46%)**
	Demographic	-	4 (0.39%)	2 (0.19%)	5 (0.49%)	**11 (1.08%)**	-	4 (1.16%)	1 (0.29%)	3 (0.87%)	**8 (2.32%)**
	Technological	7 (0.69%)	4 (0.39%)	-	39 (3.85%)	**50 (4.93%)**	1 (0.29%)	1 (0.29%)	1 (0.29%)	14 (4.07%)	**17 (4.94%)**
	Governance-Market interactions	-	-	-	0.004 (0.39%)	**4 (0.39%)**	-	-	-	3 (0.87%)	**3 (0.87%)**
Earth´s natural cycles		9 (0.89%)	6 (0.59%)	-	3 (0.29%)	**18 (1.77%)**	3 (0.87%)	1 (0.29%)	-	2 (0.58%)	**6 (1.74%)**
Don´t know		1 (0.09%)	-	1 (0.09%)	7 (0.69%)	**9 (0.89%)**	2 (0.58%)		2 (0.58%)	5 (1.45%)	**9 (2.62%)**
Total[2]		**293 (28.89%)**	**177 (17.45%)**	**137 (13.51%)**	**407 (40.14%)**	**1014 (100%)**	**108 (31.39%)**	**76 (22.09%)**	**43 (12.5%)**	**117 (34.01%)**	**334 (100%)**

3.2. Climate Change Networks (CCN)

The experts' CCN included 68 active nodes and 1142 ties, corresponding to a normalized score of 34.6 ties, with an average of 6.5 ties/respondent. The non-experts' CCN included 52 active nodes and 312 ties, corresponding to a normalized score of 24 ties, with an average of 4.9 ties/respondent. The normalized value of the network density score of the experts' CCN (0.113) was higher than the normalized value of the network density score of the non-experts´ CCN (0.031), implying that experts reported more cascading effects than non-experts (Table 4.3). Network centralization outdegree scores were low for experts and non-experts' (3.29% and 2.01% respectively), indicating that there was not a defined small core group of impactful environmental changes generating most cascading effects, but rather that there were many environmental changes generating additional cascading effects. However, network centralization scores for indegree of experts and non-experts were higher (5.96% and 4.49% respectively), indicating a concentration of cascading effects over a group of nodes. The non-experts' CCN showed a lower network centralization betweenness score (0.45%) than the experts' CCN (3.30%), indicating that non-experts perceived less intermediate cascading effects than experts.

Table 4.3. Measures of experts' and non-experts' climate change (CCN) and global change networks (GCN). Values for ties, density, and network centralization outdegree, indegree and betweenness measures are normalized.

Attributes	**Climate change network (CCN)**		**Global change network (GCN)**	
	Experts (n=175)	Non-experts (n=63)	Experts (n=175)	Non-experts (n=63)
Nodes (n)	68	52	72	60
Ties (*total n*)	34.61 (*1142*)	24 (*312*)	14.60 (*987*)	11.18 (*329*)
Density (*d*)	0.113	0.031	0.082	0.027
Network centralization *Outdegree* (%)	3.29 %	2.01 %	9.26%	7.75%
Network centralization *Indegree* (%)	5.96 %	4.49 %	1.43%	1.51%
Network centralization *Betweenness* (%)	3.30 %	0.45 %	-	-

Regarding node measures, we found that eight out of the 10 nodes with higher outdegree scores, i.e., generating cascading effects, in the experts' and non-experts' CCN were the same (Table 4.4). Overall, changes affecting elements of the climatic and physical systems were perceived as generating most cascading effects. These included Changes in frequency of rainy days, Changes in amount of rainfall in a given season, Changes in the duration of high mountain springs, Changes in amount of snowfall, and Changes in mean temperature. Changes in crop diseases and pests, a change affecting an element of the human system, was also reported among those generating most cascading effects (Figure 4.2).

Table 4.4 List of 10 environmental changes with the highest node outdegree (i.e., number of changes generated by a node), indegree (i.e., number of cascading effects listed) and betweenness (i.e., number of times a node rests on a short path connecting two other nodes which are disconnected) scores in experts' and non-experts' climate change networks (CCN).

Order	Outdegree		Indegree		Betweenness	
	Experts	Non-experts	Experts	Non-experts	Experts	Non-experts
1	Freq. rainy days	Amount of rainfall in a given season	Crop productivity	Crop productivity	Duration of high mountain springs	Duration of seasons
2	Amount of rainfall in a given season	Duration of high mountain springs	Pasture productivity	Duration of irrigation water	Pasture productivity	Duration of high mountain springs
3	Duration of high mountain springs	Mean temperature	Duration of irrigation water	Human health (weather inclemency, insect´s bites, physical effort for NNRR)	Altitudinal distribution terrestrial fauna	Duration of irrigation water
4	Amount of snowfall	Amount of snowfall	Crop mortality rate	Crop mortality rate	Crop productivity	Duration of snow-cover
5	Unusual temperatures in a given season	Freq. rainy days	Livestock health (diseases, pests, abortions, dehydration)	Crop diseases and pests	Growth rate wild flora	Amount of snowfall
6	Mean temperature	Duration of irrigation water	Crop diseases and pests	Duration of seasons	Crop diseases and pests	Crop flowering fruiting and maturation periods
7	Duration of seasons	Duration drought periods	Honey production	Crop flowering fruiting and maturation periods	Amount of rainfall in a given season	Pasture productivity
8	Duration of irrigation water	Heat waves	Duration drought periods	Duration of high mountain springs	Duration of irrigation water	Soil humidity
9	Crop diseases and pests	Crop diseases and pests	Flowering time in wild plants	Duration drought periods	Duration of snow-cover	Duration drought periods
10	Duration of snow-cover	Duration of seasons	Duration of high mountain springs	Duration of snow-cover	Duration of seasons	Heat waves

Six of the 10 nodes with highest indegree scores (i.e., being listed as cascading effect) were the same in the expert and the non-expert CCN. Moreover, both experts and non-experts considered Changes in crop productivity as the environmental change being most impacted by other changes in our list. In both CCN, five out of 10 nodes with highest indegree belong to the human system, with non-experts considering Changes in human health as the third most affected node. Other nodes with high indegree scores belong to the physical system, and particularly relate to the water cycle (i.e., Changes in the duration of irrigation water, snow cover, high mountain springs or Changes in temporal rivers). Some nodes with high indegree referred to elements of the climatic system like Changes in the duration of drought periods (Table 4.4, Figure 4.3). Only in the experts CCN, changes in elements of the biological system appeared among the 10 nodes with highest indegree. In particular, Changes in flowering time in wild plants occupied a central position in the experts' CCN, with several ties to other changes. Non-experts´ gave less attention to changes on elements of the biological system, which occupied a peripheral position, and reported more impacts on human health (Figure 4.3).

The experts and non-experts' CCN shared five out of the 10 nodes with the highest betweenness scores. These included environmental changes related to the water cycle which also had a high indegree score (Table 4.4). Nodes representing changes on elements of the climatic and physical systems had the highest betweenness scores in the non-experts' CCN. Among experts, two nodes representing changes on elements of the biological system (Changes in altitudinal distribution of terrestrial fauna and Changes in growth rate of wild flora) and three nodes representing changes on elements of the human system (i.e., Changes in crop productivity, Changes in pasture productivity and Changes in crop diseases and pests) also had high betweenness scores (Figure 4.4).

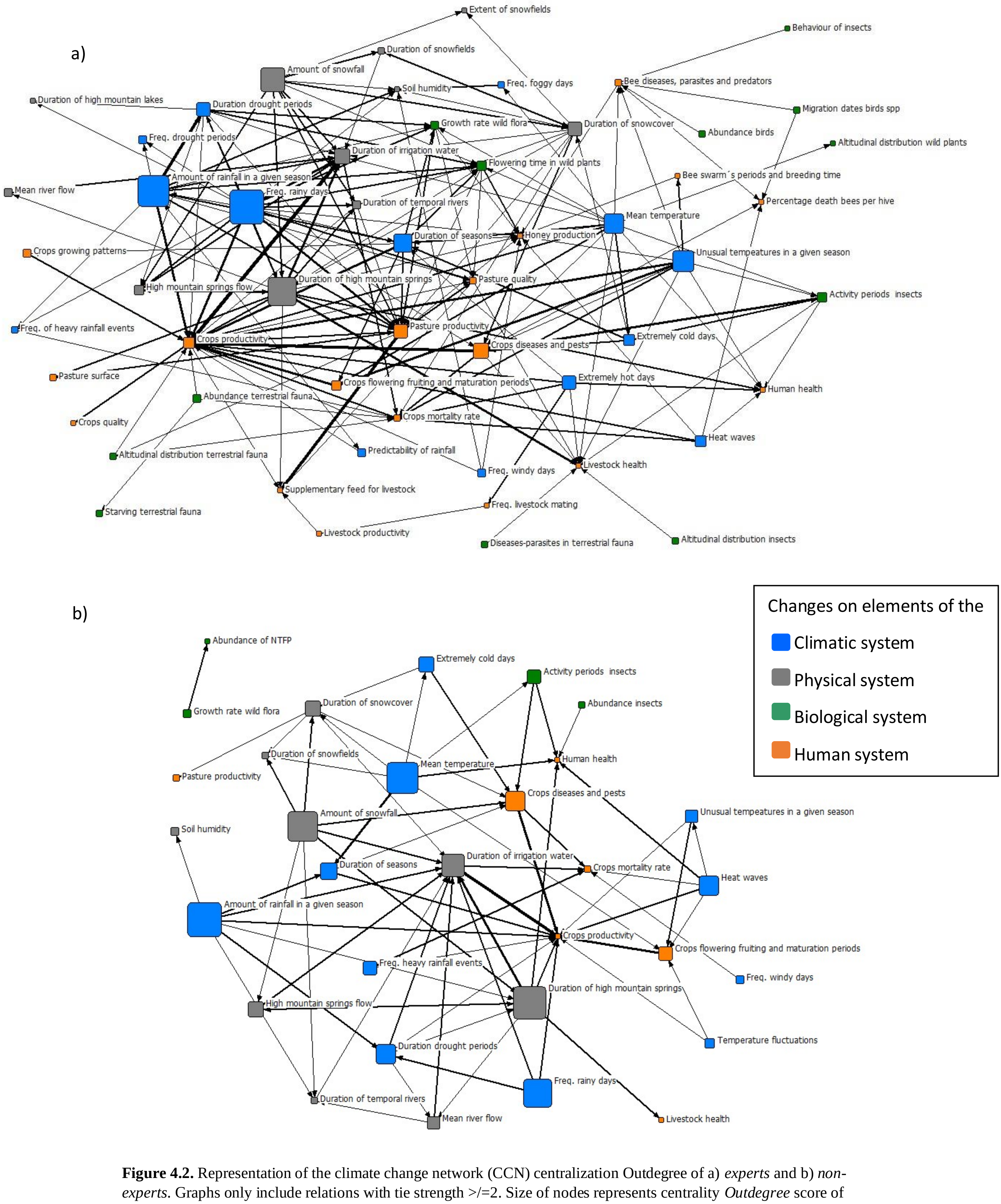

Figure 4.2. Representation of the climate change network (CCN) centralization Outdegree of a) *experts* and b) *non-experts*. Graphs only include relations with tie strength >/=2. Size of nodes represents centrality *Outdegree* score of each node. Line thickness represents the strength of the tie based on the number of respondents that mentioned the cascading effect and it has been adapted to a scale from 1 to 3.

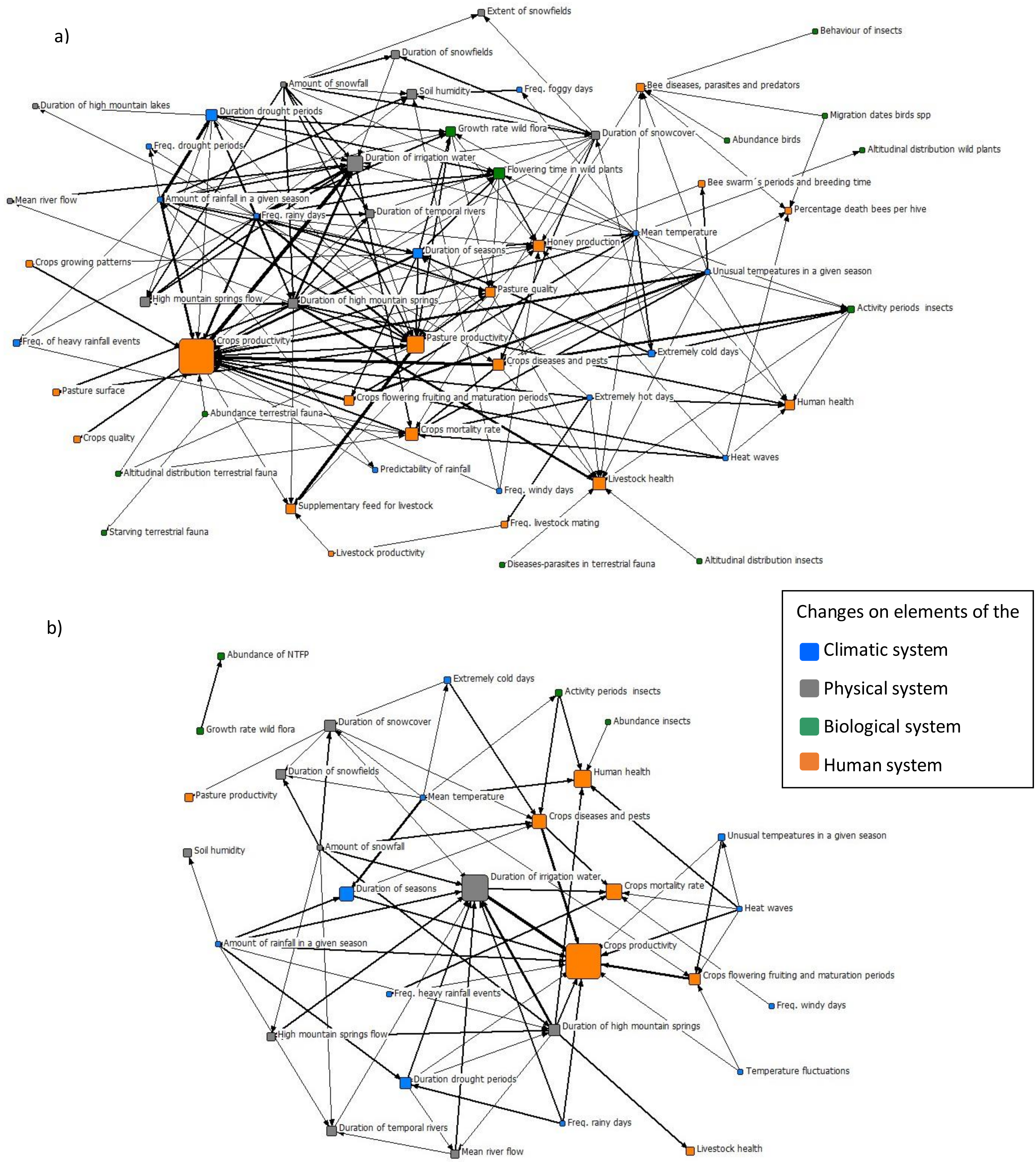

Figure 4.3. Representation of the climate change network (CCN) centralization Indegree of a) *experts* and b) *non-experts*. Graphs only include relations with tie strength >/=2. Size of nodes represents centrality *Indegree* score of each node. Line thickness represents the strength of the tie based on the number of respondents that mentioned the cascading effect and it has been adapted to a scale from 1 to 3.

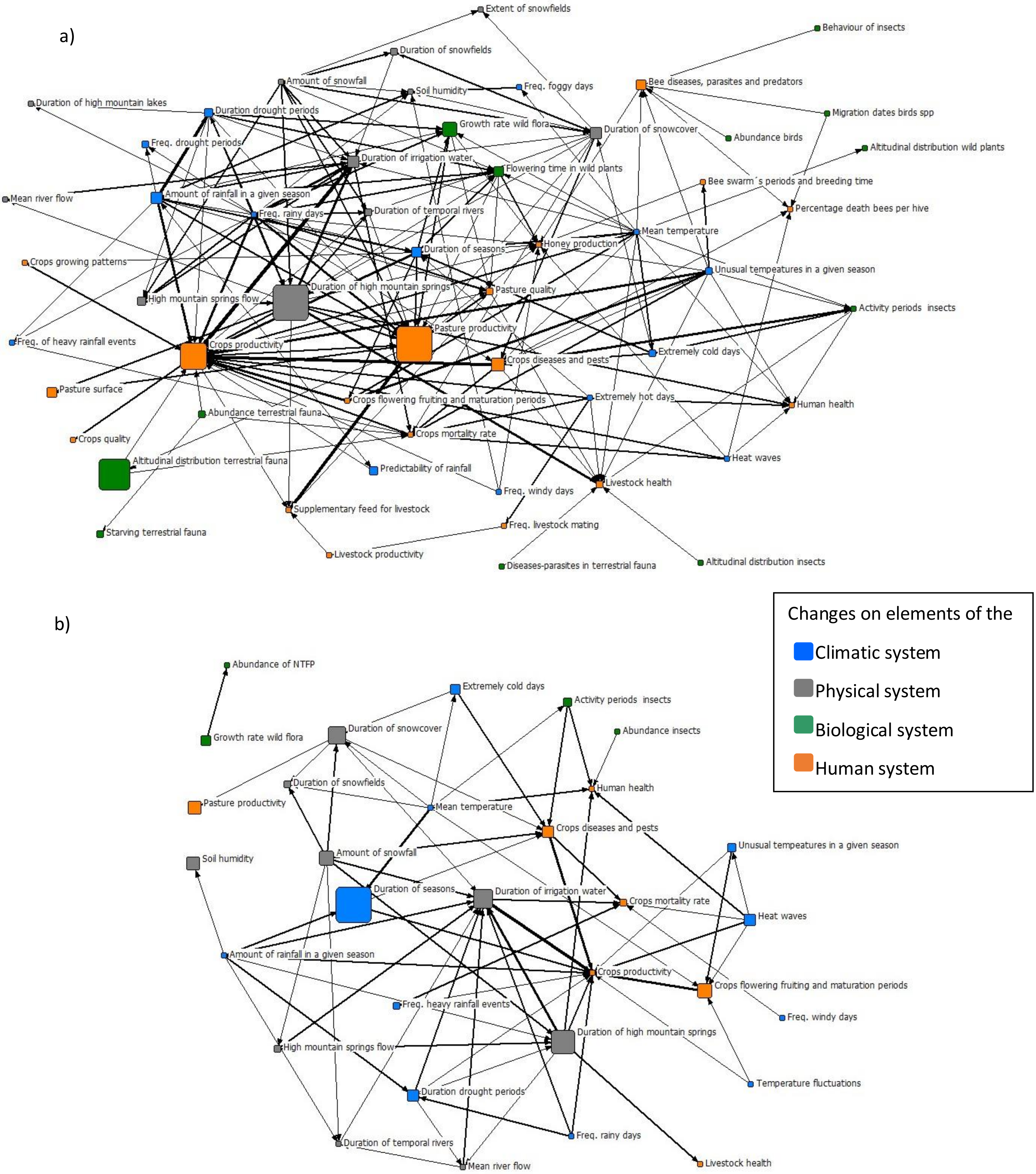

Figure 4.4. Representation of the climate change network (CCN) centralization Betweenness of a) *experts* and b) *non-experts*. Graphs only include relations with tie strength >/=2. Size of nodes represents centrality *Betweenness* score of each node. Line thickness represents the strength of the tie based on the number of respondents that mentioned the cascading effect and it has been adapted to a scale from 1 to 3.

3.3. Global Change Networks (GCN)

The number of ties and the density score of experts and non-experts' GCN (0.082 and 0.027 respectively) were lower than for CCNs. In the experts' GCN, there were 987 ties among environmental changes and drivers of these changes, which corresponds to a normalized score of 14.60 ties. The number of ties in the non-experts GCN was of 329, with a normalized score of 11.18 ties. The network centralization outdegree of the experts (9.26%) and non-experts GCN (7.75%) indicated that some drivers were more reported than others. On the contrary, network centralization indegrees of experts (1.43%) and non-experts (1.51%) GCNs were low, suggesting a dispersed distribution of environmental changes across the lists. In other words, the network centralization outdegree and indegree scores suggested that a few drivers produce many environmental changes (Table 4.3). A more detailed analysis of the outdegree scores of the nodes shows that nodes on both expert' and non-experts' GCNs were distributed around two cores. The first core centred around climate change, which generated mainly changes in the climatic and the physical systems and was considered the most important driver by experts and non-experts. The second core included all the other drivers, with conservation policies as the second most important driver of change. Experts considered technological changes as the third most important driver of change, while non-experts pointed to the effect of land use change produced by the abandonment of crop fields. This second core also included most changes on elements of the biological and human systems, which are simultaneously affected by different drivers of change (Table 4.5 and Figure 4.5). The representation of the experts' GCN suggests that different drivers act simultaneously generating impacts in the four systems, whereas in the non-experts' GCN we only found simultaneous effects of different drivers on changes on elements of the human system and on changes in the duration of irrigation water. In the experts' GCN, while climate change drives many changes, several environmental changes in the biological and physical systems were also attributed to other drivers such as conservation policies, technological changes, and pollution. In the non-experts' GCN, found simultaneous effects of climate change, conservation policies, land use change and technological changes mainly in Changes in crop disease-pests, Changes in crop mortality rate and Changes in crop productivity (Figure 4.5).

Table 4.5. Drivers with the highest node outdegree scores and environmental changes with the highest node indegree scores in the experts and non-experts Global Change Networks (GCN).

Order	Drivers outdegree		Environmental change indegree	
	Experts	Non-experts	Experts	Non-experts
1	Climate change	Climate change	Crop diseases-pests	Crop diseases-pests
2	Governance	Governance	Duration of irrigation water	Duration of irrigation water
3	Technological changes	Land use change	Crop productivity	Human health
4	Pollution	Technological changes	Abundance terrestrial fauna	Mean temperature
5	Land use change	Pollution	Freq. rainy days	Amount of snowfall
6	Invasive alien species	Demographic	Amount of rainfall in a given season	Amount of rainfall in a given season
7	Demographic	Invasive alien species	Pasture productivity	Duration drought periods
8	Resource extraction	Market interactions	Duration of high mountain springs	Freq. rainy days
9	Market interactions	Resource extraction	Bee diseases, parasites and predators	Crop mortality rate
10	----	----	Mean temperature	Abundance terrestrial fauna

Six of the 10 nodes with highest indegree scores were the same in experts' and non-experts GCN. Moreover, experts and non-experts perceived Changes in crop diseases-pest and Changes in the duration of irrigation water as the two most important environmental changes affecting their livelihood activities. However, experts considered Changes in crop productivity and Changes in abundance of terrestrial fauna as the next most important changes affecting them, instead non-experts considered Changes on human health and Changes in mean temperature (Table 4.5). Finally, experts perceived more synergistic effects of drivers of environmental change than non-experts. Experts perceived that seven out of the 10 nodes with highest indegree scores were generated by multiple drivers, versus three nodes perceived by non-experts (Figure 4.6). Moreover, experts perceived synergistic effects of drivers in 15 nodes belonging to the four systems, while non-experts only perceived this synergistic effect in four nodes, three of them related to crops.

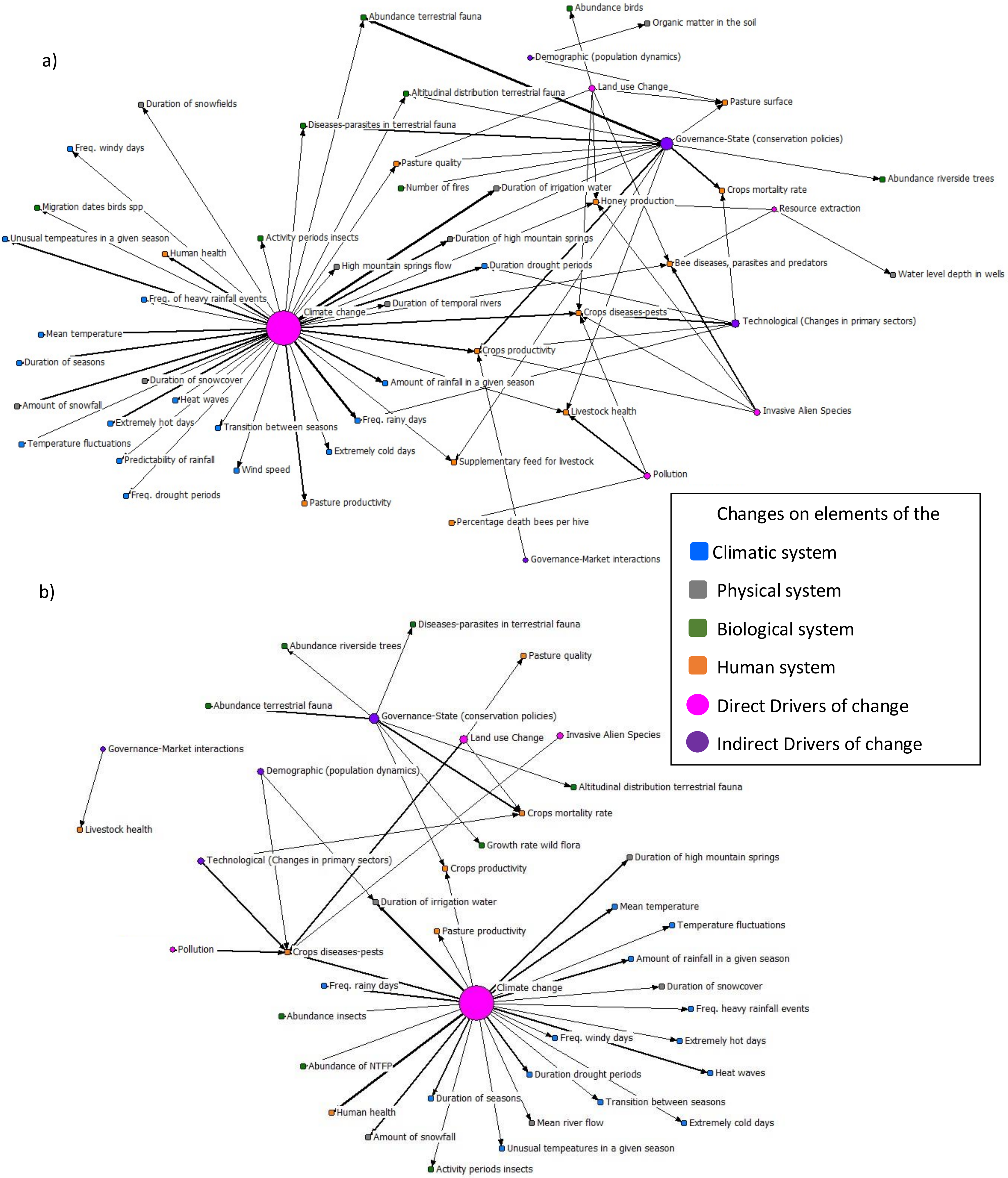

Figure 4.5. Representation of the Global Change Network (GCN) centralization Outdegree of a) *experts* and b) *non-experts*. Graphs only includes relations with tie strength >/=2. Size of node represents centrality *Outdegree* score of each node. Line thickness represents the strength of the tie based on the number of respondents that mentioned the cascading effect and it has been adapted to a scale from 1 to 3.

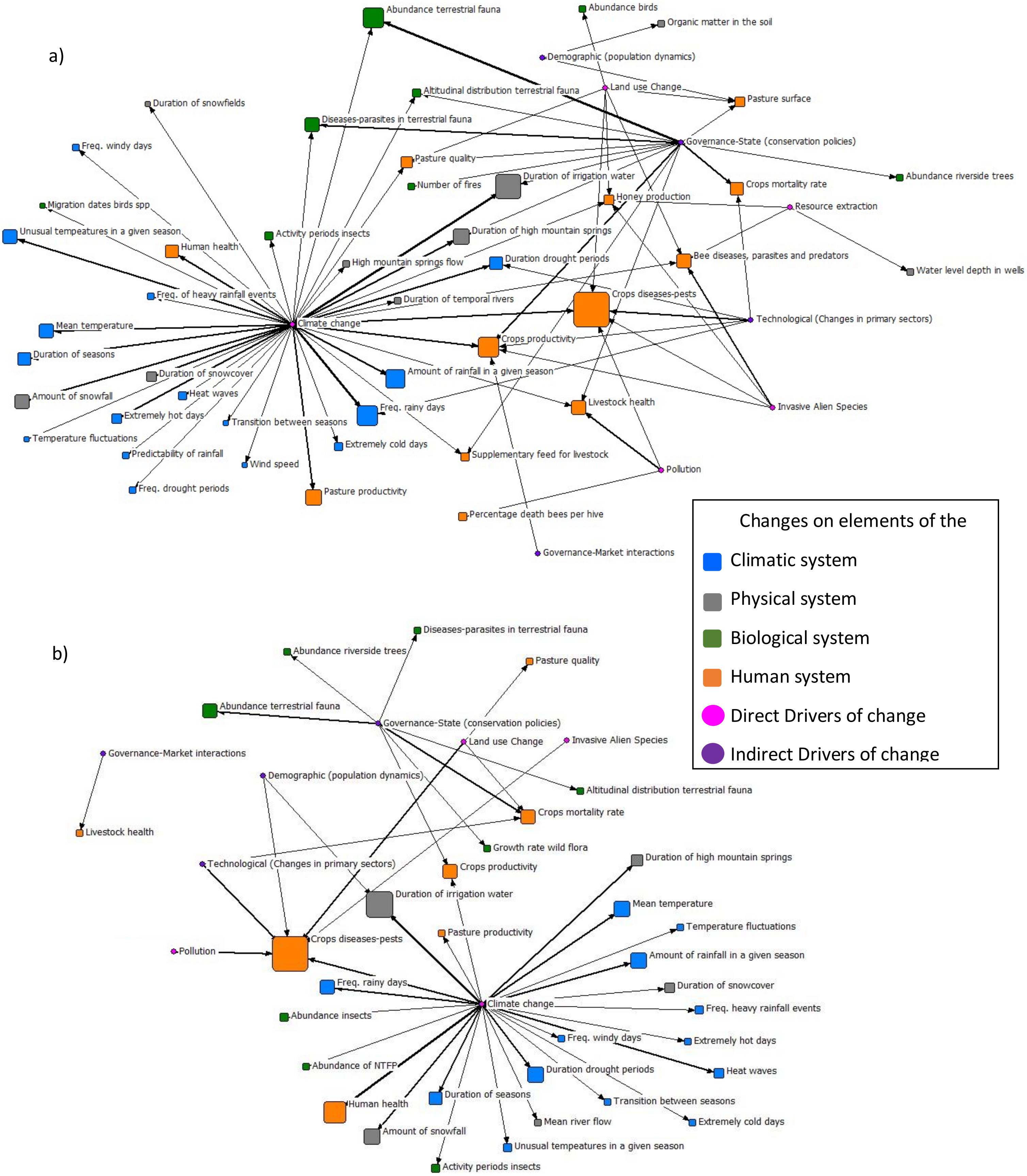

Figure 4.6. Representation of the Global Change Network (GCN) centralization Indegree of a) *experts* and b) *non-experts*. Graphs only includes relations with tie strength >/=2. Size of node represents centrality *Indegree* score of each node. Line thickness represents the strength of the tie based on the number of respondents that mentioned the cascading effect and it has been adapted to a scale from 1 to 3.

4. Discussion

We derive four main findings from the work presented here. First, Sierra Nevada inhabitants perceive many of the environmental changes driven by climate change, which are also perceived by other IPLC in mountain regions around the world. Second, respondents perceive climate change as the main driver of such environmental changes, although they also pointed at the effect of other drivers of change. Third, respondents perceive many cascading effects, mainly from elements of the climatic and physical systems to elements of the biological and human systems. Finally, informants devoted to agricultural and livestock activities (in this work referred to as experts) perceived more environmental changes, cascading effects, and synergistic interactions between climate and other drivers of change than informants not fully devoted to these activities (referred to as non-experts).

Before explaining these results, we discuss two main limitations of this work. First, we acknowledge that our sample is biased. Although we aimed to collect data from a sample stratified across different livelihoods, age and gender, this was not always possible. Importantly, most women approached refused to participate, arguing that men were responsible for farming activities. Overall, only 16 women completed our survey. Previous work has shown that men and women have different perceptions regarding environmental impacts (Gustafson 2006; Martino 2008) or ecosystem services (Martín-López et al. 2012), for which our sampling bias does not allow us to generalize results to all the population. Consequently, when interpreting the results, it should be kept in mind that they mainly capture men's perceptions. Second, our results do not necessarily capture all environmental changes affecting the local population. As explained in the methods section, our initial list of environmental changes was derived from a literature review on environmental changes driven by climate change and in our survey, we asked informants if they had observed the environmental change and their perception of potential drivers. Consequently, our findings do not preclude the occurrence of other environmental changes, particularly those mainly driven by factors other than climatic change, which might be underrepresented in this work. Moreover, our results do not exclude the possibility that when taking all environmental changes into account –i.e., including the ones not captured here-, other drivers of change might gain in relevance. Keeping these limitations in mind, we next move to the discussion of our main findings.

The first finding if this work is that Sierra Nevada inhabitants identified a large number of environmental changes affecting their social-ecological system and livelihood activities. In fact, respondents indicated environmental changes that had not appeared in our review of the literature at local scale, showing a depth level of familiarity with the environment. The finding is neither surprising nor new. It is growingly acknowledged that IPLC with a long history of interaction with the environment are able to perceive changes on their social-ecological system, for which several researchers have argued that local populations can contribute to better understand local climate change impacts (Krupnik et al. 2010; Cramer et al. 2014; Hansen et al. 2016; Maldonado et al. 2016; Belfer et al. 2017; Díaz et al. 2019; Reyes-García et al. 2019). However, differently from previous work focusing on perceptions of impacts on elements of the climatic and physical systems (Mclean 2010; Savo et al. 2016; Reyes-García et al. 2019), our respondents perceived a large number of changes in elements of the biological and –particularly- of the human systems. It is possible that previous work focusing on impacts on elements of the climatic and physical systems is just biased by a the pressure in the scientific community to validate local perceptions against climatological data (Smith et al. 2017; Roue & Nakashima 2018). Despite this trend, a recent study shows that climate change researchers consider that local information on changes on elements of the biological and human systems present the largest opportunity to improve current knowledge on climate change impacts at the local level (García-del-Amo et al., 2020). Indeed, several works report local perceptions of changes on elements of the biological and human system, such as phenological variations in agricultural crops and in wild fauna and flora species (Bollig & Schulte 1999; Clifton & Turner 2009; Li et al. 2013; Klein et al. 2014; Armatas et al. 2016), or changes in the location and time of migratory routes (Riseth et al. 2011; Nakashima et al. 2012; Huntington et al. 2017). Similarly, respondents in Sierra Nevada perceived many changes in elements of the biological system including phenological changes, changes in the appearance of diseases, changes in crop productivity, changes related to livestock, pastures, and bees, and changes in the abundance and altitudinal distribution of wild boards and Iberian ibex (*Capra pyrenaica*). Indeed, the change on abundance and altitudinal distribution of the Iberian ibex reported by our informants is in concordance with information published in the last census, showing that Iberian Ibex population in Sierra Nevada has increased more than 10 times in the last 60 years (Granados et al. 2020). This overlap suggests the possibility of bridging information derived from the two sources of knowledge in future efforts to monitor changes in elements of the biological system.

The second finding of this work is that while respondents perceived climate change as the main driver of the environmental changes listed, they also pointed at the effect of other drivers of change. Among the other drivers of change mentioned, informants mentioned land use change produced by abandonment of crop's fields, pollution from pesticides, conservation policies, technological changes in primary sectors, population dynamics, invasive alien species, resource extraction and market interactions. Indeed, the analysis of the GCN suggests that responses were organized in two interrelated cores: one core included climate change as main driver of change and the other core included the other eight drivers of change, among which respondents highlighted conservation policies. Both cores interact one to another potentially generating synergistic impacts. For example, the increase of wild boards and Iberian ibex populations due to conservation policies, together with the reduction of natural resources due to climate change impacts result in economic and material losses to farmers and ranchers of Sierra Nevada. A similar result has been reported in relation to reindeers in Norway, elephants in India, or wild carnivores in other areas of the world (Pecl et al 2017). Similarly, the synergistic impact of forest conservation policies and land use change produced by abandonment of field crops resulting in the reduction of surface pasture available both for livestock and other herbivores has also been reported in other protected areas (Khan & Bhagwat 2010; Martín-López et al. 2011; Guadilla-Sáez et al. 2019). Moreover, these changes also interact with other climate change impacts, such as changes in the altitudinal distribution of wild fauna, which impels wild fauna to invade crop fields to feed and drink, and favours the transmission of diseases to livestock, which are slaughtered to the detriment of the rancher or shepherd, since livestock could act as transmission vectors to the human population as happened previously (Seleem et al. 2010; Morse et al. 2012; Pagabeleguem et al. 2012; Bouyer et al. 2013). Respondents also recognized that pollution from pesticides and technological changes in primary sectors produced, together with climate change, severe impacts in human systems of Sierra Nevada. The excessive use of pesticides greatly affects ecosystems, including the contamination of soils and aquatic ecosystems or the generation of diseases and death of plant and animal species, including cattle and bees (Woodcock et al. n.d.; Sánchez-bayo et al. 2011; Mahmood et al. 2016; Díaz et al. 2019; Quesada 2019; Arneth et al. 2020). Similar impacts were described by our respondents, who also mentioned the effects of the introduction of new crop varieties, highly input-dependant. Moreover, respondents considered that new varieties are less resistant against the increasing abundance of diseases and pest, which are enhanced by the increase in mean temperature generated by climate change (Burgess et al. 2014; Füssel et al. 2017).

The study of the interaction between climate change and other drivers of change and the amplifying impacts of interactions between drivers has recently captured researcher’s attention (e.g., (IPCC & IPBES 2020; Arneth et al. 2020). Researchers have noted that the interactions between drivers is not uniform, for which the synergistic impacts are unevenly manifested in the territory (Brook et al. 2008; Rocha et al. 2015). In that sense, and given the inherent difficulty of using modelling techniques to predict interactions between drivers at the local level, local knowledge should be considered as a fundamental source of grounded information to assess the synergistic impacts of different drivers of change at a local scale (Huntington et al. 2015; Rathwell et al. 2015; Belfer et al. 2017), and potentially to discern the relative weight of different drivers (Gómez-Baggethun et al. 2013; Rosenzweig & Neofotis 2013).

The third important finding of this work is that respondents perceive many cascading effects, mainly from elements of the climatic and physical systems to elements of the biological and human systems, ultimately affecting livelihood activities. Respondents to our survey considered that changes on temperature, snow, water, but also on crop diseases and pests and pasture productivity generated several other environmental changes, or cascading effects. Due to the importance and magnitude of its cascading effects, water availability is considered a very impactful environmental change in other mountainous areas around the world (Nolin 2012; Joshi et al. 2013; Postigo 2014; Konchar et al. 2015; Ingty 2017). Therefore, in Sierra Nevada, special attention should be paid to maintaining traditional irrigation systems, which allow the supply of water to agricultural and inhabited areas on the slopes of the mountain, while maintaining the state of the high mountain meadows during the summer favours a greater biodiversity of wild flora, and offers water supply areas for wildlife and livestock of the local population (Pulido-Bosch & Sbih 1995; Jódar et al. 2017; Martos-Rosillo et al. 2019). Similarly, the increase in average temperature is another change with important cascading impacts. For example, in British Columbia or the North of Europe researchers report that the increase in average temperature allows a higher percentage of insects to survive in winter, increasing the abundance of pests and diseases in wild flora (Burgess et al. 2014; Füssel et al. 2017). According to our respondents, temperature increase also affects the quantity, quality and the survival of crops and orchards. In the same line, shepherds in the area mentioned that pasture areas are disappearing quickly, and that some pasture areas are not accessible anymore due to the reduction of number of natural high-mountain springs and excessive growth of scrubs and abundance of reforested trees (see also Ruiz-Morales et al. 2020). Identifying which environmental changes generate more cascading effects can help in the design of management plans that minimize the effect of such changes to maintain the resilience of the social-ecological systems (Xu et al. 2009; Johnson et al. 2011; Ingty 2017; Lawrence et al. 2018). This might be of particular importance in mountain ecosystems, where cascading effects tend to be more dramatic because many species are distributed in altitudinal zones that represent the limits of their survival ranges, for which variations in environmental conditions can lead to their disappearance (Illán et al. 2012; Pauli et al. 2012; Freeman & Class Freeman 2014).

The last important finding of this work is that informants devoted to agricultural and livestock activities (i.e., experts) perceived more environmental changes, cascading effects, and synergistic interactions between climate change and other drivers of change than informants not devoted to these activities (i.e., non-experts). Although both groups perceived changes in the climatic and physical systems as the trigger of most of cascading effects described, experts denoted a deeper understanding of ecological functioning of ecosystems of the region because they identified more cascading effects on elements of the biological systems. In contrast, non-experts focused their attention on elements of the human system, mainly related to crops and human health. Moreover, experts included changes on elements of the biological system, such as changes on the altitudinal distribution of terrestrial fauna and growth rate of wild flora, among the most impacted by other environmental changes-, but also among the intermediate cascading effects with more repercussion on the network. Additionally, the group of experts perceived more environmental changes related to the abundance, distribution, appearance of diseases and pests or phenological changes in wild fauna and flora than non-experts. Finally, the analysis of experts' GCN showed a higher density of ties between environmental changes and drivers, and more synergistic effects among drivers that the non-experts GCN, thus suggesting that experts had a deeper knowledge of the environmental problems affecting their social-ecological systems. In that sense, while the GCN of non-experts only included synergistic effects of different drivers on environmental changes related to crops, and duration of irrigation water, the GCN of experts showed synergistic effects of drivers on elements of the four systems, including also other environmental changes on elements from the human system, like pastures, livestock, and beekeeping.

5. Conclusion

Findings from this work show that local communities in Sierra Nevada perceive a great variety of environmental changes which they mainly attribute to climate change, while recognizing the synergies with other drivers of change. Changes on the availably of snow and water, crops, pasture, or wild herbivores are the most important impacts affecting livelihood activities of local communities of Sierra Nevada. Beyond adding to the growing number of works pointing at the importance of local knowledge systems, our findings inform local policies in at least three ways.

First, we have identified the most impactful changes as perceived by local communities. These changes could be prioritized in local adaptation plans. For example, changes in hydric resources of Sierra Nevada have an important impact in local communities, for which further efforts should be done to protect them. Importantly, because Sierra Nevada should be understood as a social-ecological system, protection should include not only the biophysical but also human components, such as irrigation communities. For example, irrigation communities, that currently manage Sierra Nevada hydric resources, could be officially included in an integrated co-management of the territory. Similarly, shepherds and ranchers should be fundamental actors in the co-management of the territory but also in the co-production of new knowledge, as their knowledge could help to monitor pasture areas affected by climate change, land use change, pressure of wild fauna or rewilding of natural areas.

Second, we have identified important drivers of environmental change beyond climate change. In that sense, conservation policies are perceived in Sierra Nevada as the largest indirect driver affecting the biological system, with economic consequences for the communities. A collaborative and inclusive solution should be consensual by all the social actors affected to avoid negative consequences for the maintenance of their traditional livelihood activities.

Third, we have shown the validity of local, particularly expert, knowledge. Local inhabitants with a dilated experience in agricultural and livestock activities have proven to be valuable holders of knowledge that should be recognized and integrated into future management plans for the region, and even more so, in the current context of climate and global change. Administration and managers of Sierra Nevada protected area should promote the co-management of the territory and co-production of knowledge with local communities regarding the main impacts identified by respondents. Local communities of Sierra Nevada have shown to be fundamental stakeholders regarding the future of the region, and their ILK should be considered as valuable source of information that should be incorporated in future co-management, climate change research and adaptation plans.

Compliance with ethical standards

This research received the approval of the Ethics committee of the Autonomous University of Barcelona (CEEAH 3581 and CEEAH 4781).

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Supplementary material

Table 4.6. List of environmental changes - partially related to climate change-, selected from the literature review, that were presented to the respondents. Climate Change Network (CCN) represents the five environmental changes selected by each respondent affecting them the most and attributed to climate change. Global Change Network (GCN) represents the five environmental impacts selected by each respondent affecting with more intensity in the region and generated by thirteen drivers of change, included climate change. Environmental changes' list was adapted from Local Indicators of Climate Change Impacts (Reyes-García 2019). Changes in *italics* represent new environmental impacts perceived by respondents and not included in the original list presented to them.

System	Subsystem	Impacted element	Environmental changes	Climate Change Network CCN	Global Change Network GCN
Climatic System	Temperature	Mean temperature	Changes in mean temperature	X	X
			Changes in temperature fluctuation	X	X
		Extreme temperature	Changes in the frequency of extremely cold days	X	X
			Changes in the frequency of extremely hot days	X	X
			Changes in the frequency of heat waves	X	X
		Seasonal temperature	Changes in the frequency of unusual temperatures in a given season	X	X
	Precipitations	Mean precipitation	Changes in the number of days with rainfall / rainy days (not further specified)	X	X
		Precipitation extremes	Changes in the frequency of heavy rainfall events	X	X
		Precipitation distribution, variability and predictability	Changes in the predictability of rainfall	X	X
		Seasonal precipitation	Changes in the amount of rainfall in a given season	X	X
		Drought	Changes in the frequency of drought events	X	X
			Changes in the length / duration of drought	X	X
		Clouds and fog	Changes in the frequency of fog or misty days	X	X
	Air masses	Wind	Changes in wind strength or speed	X	X
			Changes in the number of windy days	X	X
		Storm (wind /hail /dust /sand /electric)	Changes in the frequency of sand or dust storms	-	-
			** *Changes in the frequency of electric storms*	X	X
	Seasons	Duration and timing of seasons	Changes in the length /duration /disappearance of seasons		
			Changes in the transition between seasons		
Physical system	Freshwater	Mean river flow	Changes in river / stream water flow, volume, level and/or depth	X	X
			Changes in high mountain springs flow	X	X
		River and lake floods	Changes in the extension of the area flooded by rivers	-	-
			Changes in the frequency of river / lake floods	X	X
		Fresh water availability/quality	Changes in the duration of temporal rivers	X	X
			Changes in the duration of irrigation water	X	X
			Changes in the duration of high mountain springs	X	X
		** *Underground and phreatic water*	** *Changes in water level depth in wells*	X	X
		Water temperature of rivers and lakes	Changes in temperature of river water	-	-
		Lake / pond level	Changes in the duration of temporary lakes / ponds	X	X
		River /bank / pond erosion and sedimentation	Changes in the intensity of river or pond bank erosion	-	-

	Soil	Soil erosion/landslides	Changes in soil erosion	-	-
			Changes in the frequency of landslides	-	-
		Soil moisture	Changes in soil moisture / humidity	X	X
		Soil fertility, structure, and biology	Changes in soil fertility	-	X
	Ice and snow	Snowfall and snow cover	Changes in the amount of snowfall	X	X
			Changes in temporal distribution of snowfall	X	X
			Changes in the duration of snowfields	X	X
			Changes in the length / duration of temporary snow cover	X	X
			Changes in the extent of snowfields	X	X
		Seasonal ice formation	Changes in extent of ice in rivers and lakes	-	-
			Changes in the thickness of ice in lakes or rivers	X	X
Biological System	Fresh water biological system	Fresh water fish Abundance	Changes in the abundance of freshwater fish	-	-
		Fresh water fish Distribution and migration	Changes in the altitudinal distribution of freshwater fish	-	-
		Fresh water fish Disease/pest/mortality	Changes in the frequency of diseases in freshwater fish	-	-
			Changes in the frequency of malformations in freshwater fish	-	-
			Changes in the size of freshwater fish	-	-
		Fresh water fish Phenology	Changes in the timing of mating or reproduction of freshwater fish	-	-
	Terrestrial fauna	Terrestrial fauna Abundance	Changes in the abundance of terrestrial vertebrates	X	X
			Changes in the abundance of birds	X	X
			Changes in the abundance of insects	X	X
			Changes in the abundance of wild hives	-	X
		Terrestrial fauna spp composition (assemblage of species)	Change in the appearance of new birds	-	X
			Change in the appearance of new insects	-	-
		Terrestrial fauna Distribution and migration	Changes in the altitudinal distribution of terrestrial vertebrates	X	X
			Changes in the altitudinal distribution of birds	-	-
			Changes in the altitudinal distribution of insects	X	X
		Terrestrial fauna Disease/pest/mortality	Changes in the frequency of diseases and parasites in terrestrial vertebrates	X	X
			Changes in the frequency of malformations in terrestrial vertebrates	X	X
			Changes in the abundance of starving terrestrial vertebrates	X	X
			Changes in the frequency of diseases and parasites in birds	-	X
			Changes in the frequency of malformations in birds	-	-
			Changes in the size of birds	-	-
		Terrestrial fauna Phenology	Changes in the hibernation dates of vertebrates	-	-
			Changes in the reproduction dates of vertebrates	-	-

		Changes in the timing of migration of birds	X	X
		Changes in the reproduction dates of birds	-	-
		Changes in the activity periods of insects	X	X
		Changes in the timing of migration of insects	-	-
		** *Changes in Insects' behaviour*	X	X
Wild flora	Wild flora Abundance	Changes in the abundance of riverside trees	-	X
	Wild flora Distribution (fungi-plants-shrubs-trees)	Changes in the altitudinal distribution of wild plants	X	X
	Wild flora Disease/pest/mortality (fungi-plants-shrubs-trees)	Changes in the occurrence of diseases/plagues in wild flora	X	X
	Wild flora Phenology (fungi-plants-shrubs-trees)	Changes in wild plant species germination time	-	-
		Changes in wild plant species flowering time	X	X
	Wild flora Productivity and Quality	Changes in the growth rate of wild plant or fungi species	X	X
		Changes in the abundance of non-timber forest products	X	X
		Changes in the quality of non-timber forest products	X	X
	Wildfires	Changes in wildfire frequency	X	X
Human System – Cultivated spp	Cultivated spp productivity and quality	Changes in crop productivity / yield	X	X
		Changes in crop growing patterns	X	X
		** *Changes in the quality of crop species / products*	X	X
	Cultivated spp Disease/pest/mortality	Changes in the frequency of crop diseases and plagues (virus, fungi, bacteria, insects)	X	X
		Changes in crop mortality rates	X	X
	Cultivated spp Phenology and reproduction	Changes in crop germination and flowering dates	X	X
		Changes in crop suitable cultivation areas	X	X
Pasture and grasslands	Pasture availability and productivity	Changes in pasture productivity	X	X
		Change in the abundance of supplementary feed for livestock	X	X
		** *Changes in pasture cover, surface or abundance*	X	X
	Pasture spp composition, distribution and quality	Changes in the quality of pasture (without further specification)	X	X
Livestock	Livestock productivity and quality	Changes in livestock productivity (eg., milk, meat, wool)	X	X
		Changes in livestock products' quality	X	X
		Changes in honey production	X	X
	Livestock disease/pest/mortality	Changes in livestock health	X	X
		Changes in the occurrence of bees' diseases, parasites and predators	X	X
		Changes in bees' mortality rate	X	X
		Changes in the frequency of malformations in bees	X	X
		Changes in the frequency of livestock mating	X	X

	Livestock phenology	Changes in livestock behaviour	X	X
		Changes in time of swarm and bee breeding	X	X
	*** Human health*	*** Changes in human health (weather inclemency, weather-related illness, insect´s attacks, physical effort obtaining and collecting natural resources)*	X	X

Supplementary material

Table 4.7 Descriptive analysis of the age of the different groups of respondents.

			Age of respondents			
Group		(n)	min	max	mean	s.d
Experts	Farmers	66	37	91	60.98	13.75
	Shepherds	40	32	80	58.05	9.10
	Ranchers	13	40	65	52.38	7.96
	Beekeepers	31	33	75	54.38	9.67
	Agricultural ranchers	25	35	85	62.2	13.06
Non-Experts		63	28	84	57.49	11.72

- Conclusions -

Chapter V.
Conclusions

5. 1. Theoretical contributions

A main theoretical contribution of this thesis is to bring evidence of the importance of including ILK in climate change research to improve our understanding of climate change impacts at the local level. In that sense, this research adds new data to this still new, but growing, interdisciplinary research field that supports the urgency of including ILK and IPLC's perspectives and needs in climate change research (Berkes, 2017; Chanza and De Wit, 2016; Díaz et al., 2019; Hansen et al., 2016; Hiwasaki et al., 2014; Johnson et al., 2016; Nakashima et al., 2012; Rathwell et al., 2015; Tengö et al., 2017). As this research field is incipient in the context of Spain, this thesis presents an original contribution in that sense.

On a more specific level, the empirical chapters on this thesis advance research on the contributions of ILK to climate change research in several ways.

First, this thesis has contributed to the **development of a classification** of Local Indicators of Climate Change Impacts. Results from the literature review performed at the beginning of this research, fertilized with the opinions of climate change researchers presented in Chapter II, were used to develop a classification system that encompasses all kinds of local observations of climate change impacts based on the knowledge of IPLCs. My initial efforts were then complemented by researchers working on the topic, which later materialized in a collaborative publication included in the annexes of this thesis (Reyes-García et al., 2019). This classification fills an important knowledge gap, as no previous classification had been proposed in the literature, and thus offer a valuable tool for the international community to lay the foundations of this incipient field of research. A common system of classification seems fundamental to achieve a strong grounding for a new research discipline aiming to have international relevance in policy and decision making.

Second, this thesis has conducted the first national **assessment of climate change researchers** regarding the possibility and importance of including ILK in climate change research**,** presented in Chapter II. Intergovernmental fora propose new fields of research and lines of action, in the same way that they propose new policies. However, they do not have the authority to implement these measures at the national level, but rather national authorities have the right and responsibility to implement these proposals. In that context, it is important to know the opinion of all the stakeholders involved, including the scientific community, for a better implementation. An important result of the assessment conducted was that there is an important mismatch between the expected contribution of ILK to climate change research and the current trend found in the literature review. In Chapter II, I show that climate change researchers consider that ILK could contribute to the understanding of climate change impacts in the biological and human systems, however results from the literature review unveil that most researchers working with IPLC on climate change projects focus on observations of climate change impacts on the climatic and physical systems. Understanding this mismatch is important to adjust the expectations of the potential contributions of ILK to climate change research.

Third, this thesis also reveals the **high level of awareness** regarding climate change impacts among local communities of Sierra Nevada. Respondents perceived large number of climate change **impacts in the climatic** and **the physical** systems, but also in the **human and the biological systems**. Differently from others works (Marin, 2010; Panda, 2016; Piya Luni, 2012), I have explored perceptions of climate change impacts in the four systems simultaneously, including a methodological design that contains a similar number of indicators of impacts from each system to avoid misrepresentation of any system. I found that some indicators of change on the biological and the human systems were among the most largely perceived by respondents. Impacts in the biological systems were less perceived by the entire sample of participants. I explored deeply the perceived impacts on the biological system in Chapter III, showing that, in fact, there are still pockets of ILK where informants report a larger number of climate change impacts on the biological system. Moreover, in Chapter IV, I showed the deep understanding that ILK confers to local communities regarding climate change impacts in the social-ecological systems of Sierra Nevada studying, through network analyses, the interactions between impacts perceived by respondents. Results from the network analyses used in this work are another example that support the importance of ILK as an independent source of valuable data that could improve future climate change impact research and decision making.

Fourth, results of this thesis contribute to the understanding of differences on the perception of climate change impacts, as they suggest that **geographical setting and sociodemographic characteristics** contribute to shape perceptions. In Chapter III, I analyzed perceptions of different groups of local inhabitants of Sierra Nevada distributed in eight geographical areas of the mountain range. Results show clear differences in their perceptions according to geographical settings. These results are a clear example of the uneven impacts that climate change produces in the territory even at small scales, supporting the need of conducting climate change impacts assessments and adaptation plans at local level (Agrawal and Perrin, 2008; Klenk et al., 2017; Nakashima et al., 2012; Soriano et al., 2017). Similarity, our results show the influence of sociodemographic factors in the perception of climate change impacts, in line with other research in the region (Garteizgogeascoa et al., 2020). Thus, I found that people with higher attachment with nature and local ecosystems perceived higher number of climate change impacts than people with lower attachment. People with a longer and closer relationship with nature might have a deeper understanding of functioning of ecosystems which consequently allows them to perceive more climate change impacts. Chapter IV also shows this difference, indicating that people from the primary sector perceive more interactions among climate change impacts than people with professions that expose them less to the environment. This result highlights the importance of preserving ILK of local communities of Sierra Nevada and bridging with it scientific knowledge for better climate change assessments.

Finally, this thesis has contributed to the theoretical perspective of climate change research showing the importance of studying local perceptions of climate change impacts, but also the **relationships** among different impacts and **between climate change impacts and** impacts from other **drivers of change**. In the analysis conducted in Chapter IV, I found that impacts related to temperature, rainfall, droughts, and availability of snow and water were perceived as the main triggers of a number of changes identified in Sierra Nevada, including changes in the human system (i.e., changes on *crops, livestock* and *bees*), but also changes in the biological system (i.e., changes on the *flowering of wild plants*), and changes in the physical system (i.e., changes in *water availability)*. The network analysis of the relations of indicators of climate change also identified the important role of intermediate cascading impacts like *changes in pasture and crops productivity, crop diseases and pests, growth rate of wild flora, altitudinal distribution of terrestrial fauna, duration of high mountain springs* or *changes in availability of irrigation water,* which can destabilize the structure of the social-ecological systems more easily due to their multiple connections with other elements. Similarly, the network analysis of the different drivers of change helped visualize the importance of impacts generated by other drivers of change in the social-ecological systems of Sierra Nevada. Importantly, some of these drivers are considered more impactful than climate change, a finding with importance in the preparation of adaptation plans.

5.2. Methodological contributions

At the methodological level, this research contributes to a growing research field promoting the inclusion of ILK in climate change research as a useful source of grounded data, as valid as scientific knowledge. Particularly, this work has provided several methodological contributions.

A first methodological contribution of this work has been the systematic comparison of information extracted from a literature review with researchers' opinions regarding ILK inclusion in climate change research. The methodological description of the procedures used during the literature review (in Chapter II) will allow other researchers to further contribute to the current database, thus promoting the comparison of results.

The second methodological contribution has been to develop a questionnaire that allows to collect climate change researchers' opinions on the importance of ILK for climate research. Such a questionnaire can be used to reproduce the assessments in other regions and countries. Although intergovernmental initiatives have long emphasized the importance of and suggested the need for bridging ILK and Western science in climate change research, this is still far from being implemented. Therefore, an evaluation of the general opinion of the scientific community working on climate change should be a necessary step for the creation of policies that take into account ILK.

The third methodological contribution of this work is the classification of local observations of climate change impacts in understandable categories of indicators. Such classification should facilitate the comparison of impacts across sites, while information retains its local meaning. It is important to emphasize that the classification presented is not static and allows for modifications and enlargements as other impacts perceived by IPLC are reported. In Chapter II and in the first article included in the annexes, I explain how I collected and classified the observations found in the literature review and how the list of indicators was derived from such observations. Since the classification aims to be comprehensive, not all the indicators in the list are applicable to each site. Consequently, in Chapter III, I included the indicators most appropriated for my study site, and the selection of these LICCI was done applying the MEB approach followed along the project.

Fourth, through the different phases of this thesis, I have aimed to follow the MEB approach, contrasting different sources of knowledge and carrying out this mutual translation between sources. Thus, the observations of climate change impacts perceived by IPLC as reported in the literature review were classified with a hierarchical structure, typical of Western scientific knowledge, but maintaining the local sense. In that way, I translated local observations into indicators such as *changes in the ability to predict rainfall* or *changes in the sense of place or in the spiritual feeling* of the respondents. In a following phase (in Chapter II), I presented the list of local indicators to climate change researchers not necessarily familiar with the ILK perspective, asking through a web-survey on their opinion about the appropriateness of such indicators to contribute to climate change studies. Results from this web-survey, contrasted with results from a literature review of my study region and from semi-structured and in-depth interviews with local ILK-holders, allowed me to select the list of indicators to be applied in my research site. It is important to note that the wording used for the indicators was understood by the interviewees, at the same time that it maintained a certain scientific rigor that would allow its interconnection with scientific data. Unfortunately, a meeting with representatives of the different types of knowledge could not be materialized, for which the knowledge bridging process was not completely achieved in this thesis to be applied effectively in the territory. To complete the process, fieldwork results should be discussed by, and contrasted with the representatives of the local communities, managers of the protected area, and the local administrations in order to determine the necessary adaptation measures and the participation of the local communities in the co-production of knowledge through the monitoring of the territory and its co-governance.

Fifth, through this thesis, I have developed a fieldwork methodology to collect, and analyze local observations of climate change impacts and I applied that methodology during my fieldwork in Sierra Nevada. In Chapter III, I considered the importance of geographical micro-differences on determining climate change was generating different impacts at local level. Similarly, my methodology allowed to assess the influence of sociodemographic factors in climate change impacts perceptions. In Chapter III and IV, results reveal the influence of those sociodemographic factors that should be taken into account when considering the ILK of local communities.

Finally, in Chapter IV, I show the relevance of network analysis to study relationships among climate change impacts and the relation between different drivers of change. This methodology has proved useful to identify impacts perceived as most harmful by respondents, but also those components of the social-ecological systems most impacted by other drivers of change. The method is useful because it allows to identify the intermediated impacts that will have more repercussions on the system through cascading effects, i.e., the impacts that will generate more repercussion in the network's structure than others. Climate change is a mix of impacts and should be studied and understood in a similar way.

When conducting interdisciplinary work, researchers encounter numerous difficulties combining methodologies and creating common frameworks of understanding that allow communication between disciplines. This is accentuated in this thesis, as I aimed at the mutual understanding of different knowledge systems. During the development of this work, I noted some caveats and limitations that researchers face when working in this interdisciplinary field. First, I am aware of the limits to the literature review conducted, which could have been expanded using different keywords and including articles published in languages other than English. Moreover, classifying local observations into indicators is a complex process due to the difficulty to classify the observations and creation of categories that correctly represent those observations but with a logic compatible with scientific knowledge. Indeed, this is somehow a subjective process that can be influenced by the opinion and background of researchers doing the classification. In that sense, interdisciplinary research teams are necessary to obtain a correct balance between the different groups of indicators of the four systems, to avoid oversizing or underrepresenting any of them. One of the most difficult aspects of the work presented here was obtaining the participation of researchers from other disciplines, both answering the web survey and collaborating during field work. Similarly, during fieldwork, I found a high percentage of women who refused to participate in the survey, which probably can be explained because I am a male researcher conducting surveys in a rural context. Surely, the same field work carried out between two researchers of different genders would have achieved a greater number of female interviewees. Lastly, network analysis also supposed a difficulty when classifying the observations of impacts reported by participants in LICCI categories. Local expressions used by interviewees and the references to geographic locations or historically relevant local environmental events required a great knowledge of the different study zones of Sierra Nevada to correctly codify the full meaning of the observations described by the participants. This was solved through continuous in-depth field research, through which all the relevant data and events of an area, necessary to understand and be able to classify the impacts described, were contrasted with representatives of the town councils and other inhabitants of the same area through informal interviews and participant observation.

5. 3. Policy implications

Inclusion of ILK as an equally valid source of knowledge in climate research is an important demand of IPLC, partly channelized through intergovernmental fora. Some researchers advocate for ILK inclusion in the co-production of new knowledge on climate change, as is occurring in other fields, such as wildlife monitoring. This should lead to more inclusive public policies. In the particular case of climate change research, IPLCs should be considered fundamental stakeholders in knowledge production, since many of them live in isolated areas where the lack of scientific data is greater or in areas where climate change impacts are expected to be larger. As results of this thesis show, local people have developed knowledge systems that allow them to perceive changes in their ecosystems in great detail. Consequently, they should have the right to have their views considered in policy making (Reyes-García et al., 2021).

Although this thesis should be understood as an exploratory and preliminary step in the process of bridging ILK and scientific knowledge, its results might help in establishing more concrete actions that materialize in the inclusion of ILK in climate change policies. In the first place, the results of Chapter II show how most researchers participating in the survey recognized that there is an urgent need to collect local level data regarding biophysical systems. This finding is important because it allows to anticipate more precisely local climate change impacts. Most researchers showed a positive opinion about the possibility of including ILK in the different fields of research related to climate change, considering that their perceptions of climate change impacts on the biological and human systems would be valuable for science. In that sense, it is important to note that, given the process of rapid erosion of ILK, the communication between knowledge systems should start as soon as possible, promoting at the same time the importance of ILK in climate change studies.

Second, fieldwork results show that respondents perceived many climate change impacts, being the group of shepherds and agricultural ranchers the group of participants who perceived more impacts, particularly in the biological and human systems. Results indicating changes in the abundance of certain animal species, variations in their distribution, or changes in the mating and migratory periods suggest that a good opportunity exist to develop co-monitoring plans related with climate change impacts research which include ILK from local communities. Community-based monitoring programs engaging local communities in conservation activities are currently a reality in many places (Austin et al., 2017; Brammer et al., 2016; Min-venditti et al., 2017). A similar approach could be applied to monitor climate change impacts in IPLC territories. In Sierra Nevada, several investigations have been carried out to study the benefits of grazing in the context of climate change, for its effect as a natural firebreak and for its contribution to seed dispersal and biodiversity conservation (Kyriazopoulos et al., 2016; Robles et al., 2014, 2008; Ruiz-Mirazo and Robles, 2012; Ruiz-Morales et al., 2020). In addition, a decade ago the local administration launched an initiative to revitalize traditional professions and created a “school of shepherds”. This background is an ideal base on which to create long-term collaborations with the shepherds and ranchers of Sierra Nevada. Specifically, one could imagine creating a program to monitor the impacts of climate change co-designed and co-managed with pastoralists. Such a program would also help enhance the social perception of this profession (Ruiz-Morales et al., 2020), which would encourage its revitalization by some local young people. In the same way, representatives of the other groups of the primary sector (i.e., farmers and beekeepers) could contribute to the co-production of knowledge in agricultural research in the current climate change context (Labeyrie et al., 2021), and would also participate in decision-making related to climate change that affect Sierra Nevada, for example by providing information about the evolution of crops, variations of crops’ production, increase in the number of pests and their persistence throughout the year.

Third, results showed geographical differences related to the area in which respondents live, probably indicating that climate change is producing impacts of different intensity on the different areas of the study region. These results show the need to carry out multi-scale adaptation policies, with a general legislation with similar basic rules for all the territory, but a flexible system for lower administrative levels which should have the capacity to be defined and adapted to the reality and problems of each region and area (Burnham and Ma, 2018; Ostrom, 2010; Reyes-García et al., 2016).

Fourth, results of Chapter IV showed high level of awareness of local communities of Sierra Nevada regarding climate change impacts, the interactions between them, and the influence of other drivers of change. These findings reinforce the importance of including ILK perspective in climate change studies and policies. Local people's experience and knowledge have proven to be valuable resources that should be considered when identifying key intermediate cascading effects which can destabilize social-ecological systems, even if they are not the most intense impacts perceived in the system. However, Chapter III showed how the sociodemographic variables of respondents influenced their climate change impacts perception. As the knowledge bridging process should be carried out in a respectful way in which each knowledge system is consensual and validated by its own users using their own reference frameworks, representatives of the local communities who participate in the creation of policies should take internal differences into account when contributing with their knowledge.

Climate change policies are oriented to reduce vulnerability, but policies are done at national level, without including the local reality of small rural communities, who are going to suffer climate change impacts on the front line. Moreover, most policies are done to preserve natural ecosystems, rather than social-ecological systems, in which local communities play a fundamental role and should therefore be engaged in the co-governance of the territory, collaborating in management and monitoring and co-producing knowledge. Sierra Nevada is at a critical, but very favourable, moment to make this bridging between ILK and scientific knowledge possible. Together, the historical relationship of the communities with the territory, the relevance of the research carried out in that territory as it has been designated a Global Change Observatory, the current execution of an adaptive management project in the face of climate change (Adaptamed) aiming to make co-participants to local communities through citizen participation, and the declaration of the first Spanish law against climate change, generate an exceptional opportunity to continue taking the next steps to include the ILK in future policies against climate change.

Finally, more policies are generally needed to encourage and support the bridging of ILK and scientific knowledge. Numerous studies have been carried out at national and international level that demonstrate the importance of ILK and traditional practices for conservation of biodiversity (Berkes and Davidson-Hunt, 2006; Popova, 2014) and ecosystem services (Díaz et al., 2015), for sustainable management of natural resources (Berkes et al., 2000; Cox et al., 2010; Tschirhart et al., 2016), restoration of degraded ecosystems (Fox et al., 2017; Pyke et al., 2021). This work adds to the incipient field showing the importance of ILK in climate change research. What is needed now is greater recognition by the administration when creating public policies that recognize the importance of ILK and the need to include it as an additional knowledge system with a similar validity to scientific knowledge. In the same way, it is necessary to create policies protecting lifestyles and traditional practices that perpetuate ILK, which will help to promote its revitalization among the new generations and prevent its loss.

5. 4. Future research lines

Bridging ILK and scientific knowledge in climate change research is still an incipient field, for which there are many possible research topics unexplored.

The categorization of climate change observations can become a fundamental tool in efforts to bridge ILK and scientific knowledge. In that sense, the categorization proposed here is a first step, although it still needs to be improved and completed with more categories that represent the diversity of perceptions of the different IPLC around the world. Therefore, collaborations with other researchers and IPLC in order to improve this categorization (for example by proposing new categories or with contributions of new observations) are essential to improve this tool.

The researchers' opinion assessment conducted offered a first view of researchers' opinions on the bridging process between both knowledge systems. However, new and deeper evaluations should be made at the regional and national level seeking higher participation from researchers from the different disciplines studying climate change. These evaluations can be replicated in other countries, to find out the opinion of the rest of the scientific community, as eventually they can be allies in the creation of new climate change policies including ILK. Similarly, more studies should be carried out on a national and international scale to continue improving our understanding of IPLC perception of climate change impacts and to be able to include ILK in adaptation policies. This thesis has briefly explored the sociodemographic variables influencing respondents´ climate change perceptions, but more research is needed to fully understand how, and which factors have a higher influence in these perceptions. Additionally, more studies analysing the influence of other drivers of change on climate change impacts are needed to understand better local differences perceived by IPLC.

Finally, my research also needs to be completed to achieve a correct bridging of the two knowledge systems. In the first place, results of the statistical analyses should be commented with the local communities to verify that they consider correct the interpretation of the result, or to complement information. Ideally, representatives of local communities from the different areas of Sierra Nevada should hold meetings with the researchers working on adaptive management projects against climate change in their territory to compare the impacts detected and its distribution in the territory. Through these meetings, local communities could orient researchers on priority action measures that should be carried out on each area to compensate the impacts and maintain the resilience of the social-ecological systems of Sierra Nevada. Those communication meetings between the different stakeholders and decision makers could help define the monitoring and co-management measures necessary for the sustainability of the social-ecological systems of Sierra Nevada over time.

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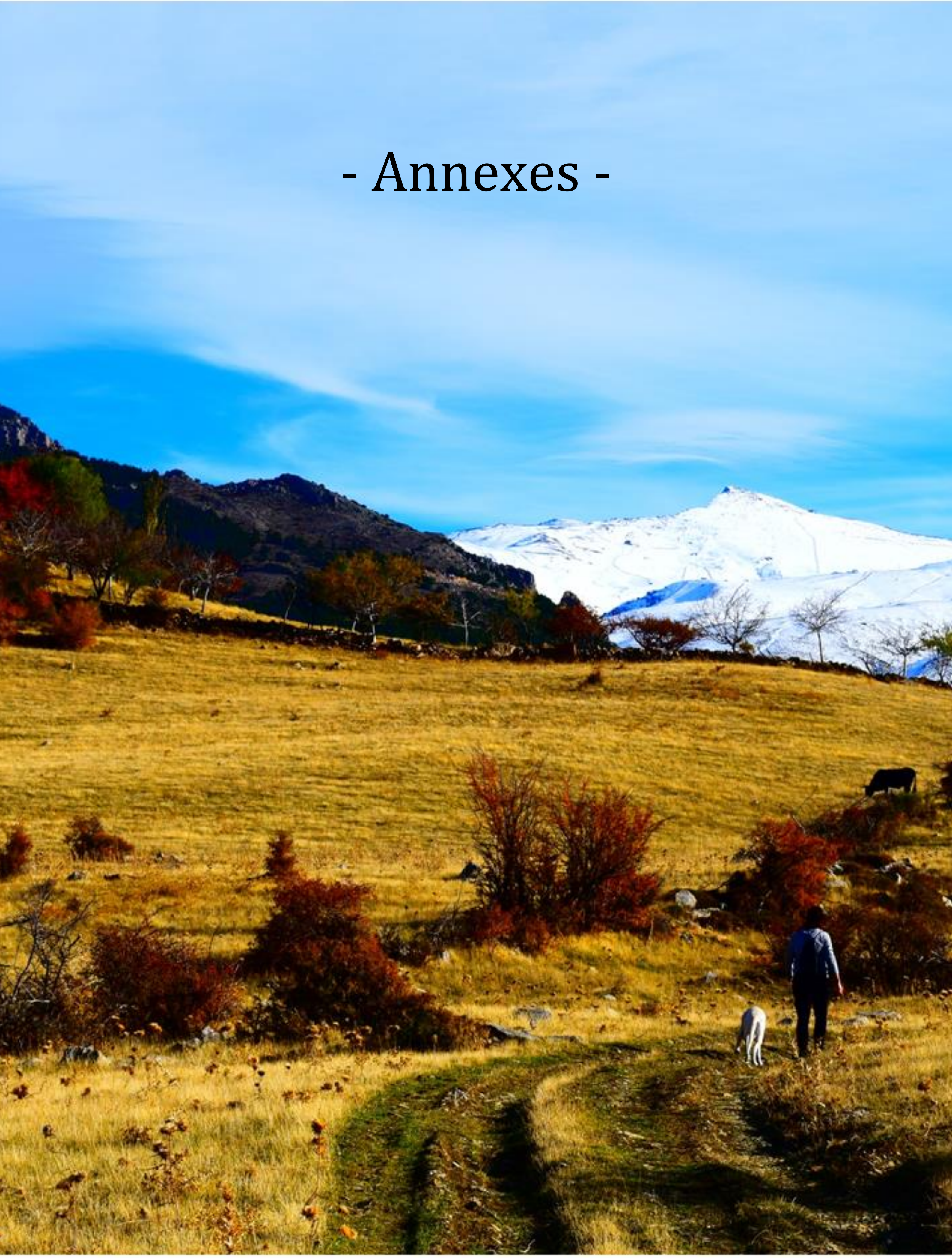
- Annexes -



Annex I

Fieldwork survey and informed consent form

HOJA INFORMATIVA

Indicadores Locales de Cambio Climático

Victoria Reyes-García es una investigadora antropóloga de la Universitat Autònoma de Barcelona, que liderará este nuevo proyecto de investigación con la ayuda de otros estudiantes e investigadores. El principal objetivo de este proyecto es conocer los cambios ambientales en su entorno local y cómo estos cambios afectan su vida diaria. Para ello, haremos preguntas a la gente en el pueblo sobre los cambios en la época de germinación y floración de plantas, el comportamiento y la abundancia de los animales o cambios relacionados con en el suelo, agua y hielo. Para recopilar esta información, nos gustaría pedir su participación en un breve cuestionario. Los datos generados en este estudio se usarán únicamente para investigación, no se usarán con ningún propósito comercial. Esta investigación está financiada por el Consejo Europeo de Investigación a través de una beca de consolidación a Victoria Reyes-García y los fondos son administrados por la Universitat Autònoma de Barcelona.

Procedimientos y duración: Los investigadores vivirán en la zona de estudio y le visitarán para hacerle preguntas sobre los cambios que ha presenciado en el entorno y cómo le afectan personalmente. La duración de cada visita será de aproximadamente treinta minutos- una hora. Si decide participar en el estudio, su participación implicaría: contestar un cuestionario que incluye preguntas sobre usted (p.ej. edad, tiempo viviendo en la comarca, profesión…), preguntas sobre su relación con el entorno natural, preguntas sobre su trabajo en el campo (agricultura, ganadería o silvicultura), y los cambios ambientales que ha percibido en el entorno que vive. Todos los procedimientos elegidos para este estudio son ampliamente utilizados por los antropólogos y conllevan riesgos mínimos.

Protección de datos: sus datos personales solo estarán disponibles para el personal principal del proyecto y serán completamente confidenciales (es decir, nadie podrá identificarlo). Ninguna publicación o informe identificará a los encuestados por su nombre. Los datos no se usarán para ningún otro propósito que no sean publicaciones científicas. Los datos no se venderán, darán o transferirán de ninguna otra forma a terceros que puedan usarlo con otro fin que no sea la investigación. Incluso en este caso, nos aseguraremos de que los terceros no puedan identificar a la persona que proporcionó los datos. La información sobre los cambios locales percibidos en el entorno se cargará en una plataforma web, de modo que cualquier persona interesada pueda consultarla.

Participación: la participación en la investigación es estrictamente voluntaria, y todas los encuestados deberán dar su consentimiento libre, previo e informado antes del inicio de la investigación. También tendrá derecho a retirarse de la investigación en cualquier momento que lo desee. No hay pagos individuales por participar en el estudio, pero los participantes se beneficiarán de esta investigación en dado que creemos que el proyecto de investigación servirá para empoderar a las personas y pueblos como resultado del reconocimiento y la valoración de sus conocimientos tradicionales.

Participación en los beneficios: la información se utilizará para informar a los científicos y al público en general sobre cómo el conocimiento de comunidades de Sierra Nevada puede ayudar a diseñar mejores políticas para la adaptación al cambio climático. El proyecto ayudará a los extranjeros a obtener una mejor apreciación de la cultura local. Al final del trabajo de campo, compartiremos el conocimiento obtenido a través de esta investigación con los participantes en un taller en el que presentaremos nuestros resultados preliminares y les pediremos a los participantes que interpreten nuestros hallazgos. El enfoque permitirá la diseminación de resultados entre los pobladores y la recepción de la interpretación local de nuestros datos.

FORMULARIO de CONSENTIMIENTO INFORMADO

Estamos pidiendo su colaboración, porque usted vive en uno de los municipios seleccionados para nuestro estudio. No es necesario que participe si no lo desea, y puede dejar de hacerlo en cualquier momento. La participación en este estudio es completamente voluntaria. La única alternativa a participar en este estudio es no participar. No hay ningún tipo de sanción para las personas que deciden no participar, o que comenzaron y luego decidieron retirarse.

Los datos personales que recojamos mediante este estudio estarán disponibles solamente para los investigadores principales del proyecto y serán completamente confidenciales. Ninguna publicación o informe les identificará por su nombre. Los datos no se usarán para ningún propósito diferente a publicaciones científicas. Los datos personales no serán vendidos, cedidos ni transferidos mediante ninguna otra forma a terceros que pudieran usarlos con cualquier otro fin que no fuera investigación. Incluso en este caso, nos aseguraremos de que terceras partes no puedan identificar la identidad de la persona que nos facilitó los datos.

La información se usará para informar a científicos y el público en general acerca de los cambios que usted percibe en su zona y en qué medida le están afectando.

Victoria Reyes García es la responsable de este proyecto y usted puede realizarle cualquier consulta sobre el proyecto o los procedimientos. Ella quizás visite la zona durante el periodo de toma de datos, pero usted siempre puede escribir al Instituto de Ciencia y Tecnología Ambientales, Universidad Autónoma de Barcelona, 08193 Cerdanyola del Valles, España. También puede llamar al 93 581 89 76 o enviar un correo electrónico a Victoria.reyes@uab.cat. Si tiene cualquier pregunta acerca de sus derechos legales como sujeto de investigación, puede contactar con ceeah@uab.cat. Para contactar con ella, debe preguntar al investigador que está trabajando en la zona, quien tendrá instrucciones completas y lo hará a su favor y sin ningún coste para usted.

Mediante su disposición a participar y su consentimiento, no está renunciando a ninguno de sus derechos legales, reclamaciones o recursos. Puede firmar el formulario usted mismo o solicitar que otra persona lo firme en su nombre. Si lo prefiere, podemos registrar su consentimiento para participar grabándolo en cinta.

He leído (o alguien me ha leído) la información en el formulario de consentimiento. He tenido la oportunidad de realizar preguntas y todas mis dudas han sido contestadas para mi satisfacción. Firmando este formulario de consentimiento acepto voluntariamente participar en este estudio de investigación.

Nombre del encuestado:____.

.____ ___________________________________.

Firma del encuestado o representante legal Fecha

He explicado el motivo de la investigación al encuestado y he contestado todas sus preguntes. Creo que él/ella ha entendido la información descrita en este formulario de consentimiento y libremente aceptó participar.

Nombre del investigador/miembro del equipo de investigación:_____________________________ _______

.____ ___________________ _______

Firma del investigador/Miembro del equipo de investigación Fecha

FECHA.............................. ENCUESTADOR .... MUNICIPIO .... ID PERSONA ....

Desde el Laboratorio de Análisis de Sistemas Socio-ecológicos en la Globalización (LASEG) de la Universidad Autónoma de Barcelona (ICTA-UAB) trabajamos en analizar las relaciones entre las comunidades humanas y su medio ambiente. Mediante este proyecto tratamos de identificar los impactos climáticos, biofísicos y socioeconómicos generados por el Cambio Climático en Sierra Nevada y estudiar las medidas de adaptación utilizadas para combatir dichos efectos. Todos los datos se analizarán de forma completamente anónima y se usarán únicamente para investigaciones científicas. La participación en este estudio es totalmente voluntaria. Usted puede dejar de contestar a mis preguntas en cualquier momento.

Variables Demográficas y Relación con la zona

1. Lugar de residencia: .... **2.** ¿Hace cuantos años que trabaja o vive usted aquí?: .... años.
3. Edad............................ **4.** ¿Cuántos años ha estado viviendo fuera?....................años **5.** Género: Masculino / Femenino
6. ¿Cuál es su profesión/es actual?.. **7.** ¿Hace cuantos años se dedica al campo?...........años.
8. ¿Eran sus padres de Sierra Nevada? 0 1 2 - P / M **9.** ¿Y sus abuelos? 0 1 2 3 4
10. ¿Cuál era la profesión de su Padre/Madre?.............................
11. Considerando tanto sus actividades profesionales como las actividades realizadas para consumo propio ¿Qué actividades realizaban sus padres en el campo?
12. Y de estás, ¿Cuáles realiza usted ahora en el espacio de Sierra Nevada?

	Agricultura	Ganadería	Apicultura	Caza	P. Maderables	PFNM *
Padres (P.12)						
Encuestado (P.13)						

*Productos Forestales No Maderables: Frutos del bosque, setas, plantas medicinales...

13. En total ¿Cuántas Has tiene usted en propiedad, arrendadas o cedidas? ....ha.

14. ¿Cuál es su nivel de estudios?

□ Sin estudios formales □ Estudios primarios (hasta 14 años) □ Estudios secundarios (hasta 16-18 años)

□ Formación técnica (formación profesional) □ Formación universitaria

15. Pertenece a algún tipo de asociación o colectivo (c. de regantes, cazadores..)? SI / NO
16. ¿Cuál/es?..
....

17. ¿Considera que su actividad socioeconómica tiene que estar vinculada a esta zona? SI /NO ¿Podría realizar la misma actividad socioeconómica en otra zona con la misma efectividad? **(Preguntar sólo en caso de que la persona encuestada se dedique al sector primario)** SI / NO ¿Por qué? ....
....
....
....

18. Si no pudiera seguir desarrollando su actividad socioeconómica en esta zona, ¿Qué es más probable que hiciese?

- Cambiar de actividad o
- Seguir con la misma actividad en otra zona

(Preguntar sólo en caso de que la persona encuestada se dedique al sector primario)

En la siguiente sección estoy pidiendo a los encuestados que comparen la última década con 20-30 años atrás a la hora de comparar los cambios

Percepción de cambios ambientales

1. A continuación, le voy a comentar una serie de cambios percibidos por miembros de comunidades rurales de otras zonas en las últimas décadas, y me gustaría que -para cada uno de dichos cambios- me dijera si también lo ha percibido aquí en Sierra Nevada y si la tendencia que ha percibido en cada cambio ha sido de aumento o disminución.

Cambios en el Sistema Climático

CD	*Indicador de Impacto*	*Percibido Si / No*	*Más / menos*
101	Cambio en la temperatura media de cada estación	Si / No	+ / -
102	Cambio en el número de días extremadamente fríos	Si / No	+ / -
103	Cambio en el número de días extremadamente calurosos	Si / No	+ / -
104	Cambio en el número de olas de calor	Si / No	+ / -
105	Cambios inusuales de temperatura, fluctuación imprevista de la temperatura	Si / No	+ / -
106	Periodos de calor o frío discordantes con la época del año	Si / No	+ / -
107	Cambio en el número de días de niebla	Si / No	+ / -
108	Cambio en el número de días de lluvia	Si / No	+ / -
109	Cambio en la precipitación media por estación	Si / No	+ / -
110	Cambio en el número de días de precipitaciones extremas	Si / No	+ / -
111	Cambio en la frecuencia de precipitaciones imprevisibles	Si / No	+ / -
112	Cambio en el número de periodos de sequía	Si / No	+ / -
113	Cambio en la duración de los periodos de sequía	Si / No	+ / -
114	Cambio en la velocidad del viento	Si / No	+ / -
115	Cambio en el número de días de viento	Si / No	+ / -
116	Cambio en el número de tormentas de viento y arena	Si / No	+ / -
117	Cambio en el número de ciclones y tornados	Si / No	+ / -
118	Cambio en la duración de las estaciones Prim – Ver – Oto - Inv (marcar las que se alarguen)	Si / No	---------
119	Transición entre estaciones muy rápida Inv-Prim / Prim-Ver / Ver- Oto / Oto-Inv	Si / No	---------

Cambios en el Sistema Físico

CD	*Indicador de Impacto*	*Percibido Si / No*	*Más / menos*
201	Cambio en el número de deslizamientos de ladera	Si / No	+ / -
202	Cambio en el grado de erosión del suelo	Si / No	+ / -
203	Cambio en el grado de humedad del suelo	Si / No	+ / -
204	Cambio en la número e intensidad de los movimientos sísmicos	Si / No	+ / -
205	Cambio en el caudal medio de los ríos	Si / No	+ / -
206	Cambio en la duración de ríos temporales como barrancos y ramblas	Si / No	+ / -
207	Cambio en el caudal de fuentes y manantiales de alta montaña	Si / No	+ / -
208	Cambio en la duración de las fuentes y manantiales de alta montaña	Si / No	+ / -
209	Cambio en la duración de las lagunas temporales de las cumbres	Si / No	+ / -
210	Cambio en el número de crecidas y desbordamiento de los ríos	Si / No	+ / -
211	Cambio en la extensión que cubren las crecidas de los ríos	Si / No	+ / -
212	Cambio en la temperatura superficial de ríos y lagos	Si / No	+ / -
213	Cambio en la duración del agua de riego de las acequias	Si / No	+ / -
214	Cambio en la profundidad del nivel de agua en pozos	Si / No	+ / -
215	Cambio en el grado de erosión de los ríos	Si / No	+ / -
216	Cambio en la cantidad de nieve que cae al año (en cm o m)	Si / No	+ / -
223	¿Cuál es la cantidad máxima de nieve que ha visto caer en este pueblo? ¿Año?		
224	¿Hace cuantos años que no ha visto un año como este con relación a la cantidad de lluvia y agua?		
217	Cambio en la duración de la cobertura de nieve	Si / No	+ / -

218	Cambio en la ocurrencia de nieves en después del invierno	Si / No	+ / -
219	Cambio en la presencia de capa de hielo en ríos y lagos	Si / No	+ / -
220	Cambio en el grosor de las capas de hielo	Si / No	+ / -
221	Cambio en el tamaño de los neveros	Si / No	+ / -
222	Cambio en la duración de los neveros	Si / No	+ / -

Cambios en el Sistema Biológico

CD	***Indicador de Impacto***	***Percibido Si / No***	***Más/ menos antes/después***
300	Cambio en la abundancia de especies **(Anotar spp)**	Si / No	+ / -
301	Cambio en la aparición de enfermedades o parásitos en **mamíferos, reptiles o anfibios**	Si / No	+ / -
302	Cambio en la aparición de mutaciones/deformaciones en **mamíferos, reptiles o anfibios**	Si / No	+ / -
303	C. en número de **mamíferos, reptiles o anfibios** hambrientos o con tamaño menor del habitual	Si / No	+ / -
304	Cambio en las fechas de hibernación o letargo de **mamíferos, reptiles o anfibios**	Si / No	Antes/después
305	Cambio en las fechas de apareamiento de **mamíferos, reptiles o anfibios**	Si / No	Antes/después
306	Cambio en la distribución altitudinal de **mamíferos, reptiles o anfibios** **(Anotar spp)**	Si / No	Cota:
307	Aparición de nuevas enfermedades o parásitos en **peces**	Si / No	+ / -
308	Aparición de mutaciones/ deformaciones en **peces**	Si / No	+ / -
309	Cambio en el tamaño de los **peces**	Si / No	+ / -
310	Cambio en la fecha de aparición de los alevines de **peces**	Si / No	Antes/después
311	Cambio en la distribución en el río de los **peces** **(Anotar spp)**	Si / No	Cota:
312	Aparición de nuevas especies silvestres de **aves**	Si / No	+ / -
313	Aparición de nuevas enfermedades o parásitos en **aves**	Si / No	+ / -
314	Aparición de mutaciones/deformaciones en **aves**	Si / No	+ / -
315	Aparición de **aves** hambrientas o con tamaño menor del habitual	Si / No	+ / -
316	Cambio en las fechas de migración de **aves**	Si / No	Antes/después
317	Cambio en las fechas de apareamiento de **aves**	Si / No	Antes/después
318	Cambio en la distribución altitudinal de **aves** **(Anotar spp)**	Si / No	Cota:
319	Cambio en la abundancia de **insectos o arácnidos**	Si / No	+ / -
320	Aparición de nuevas especies de **insectos o arácnidos**	Si / No	+ / -
321	Cambio en los periodos de actividad de los **insectos o arácnidos** a lo largo del año	Si / No	+ / -
322	Cambio en las fechas de migración de **insectos**	Si / No	Antes/después
323	Cambio en la distribución altitudinal de **insectos o arácnidos** **(Anotar spp)**	Si / No	Cota:
324	Cambio en la aparición de enfermedades y plagas en **plantas, arbustos o árboles silvestres**	Si / No	+ / -
325	Cambio en los patrones de crecimiento de **plantas, arbustos o árboles silvestres**	Si / No	+ / -
326	Cambio en el periodo de germinación o floración de **plantas, arbustos o árboles silvestres**	Si / No	Antes/después
327	Cambio en la distribución altitudinal de **plantas, arbustos o árboles silvestres (Anotar spp)**	Si / No	Cota:

Cambios en el Sistema Socioeconómico

CD	***Indicador de Impacto***	***Percibido Si / No***	***Más / menos antes/después***
401	**Agricultura**----Cambio en la cantidad de producción de los cultivos	Si / No	+ / -
402	Cambio en el número de plagas de insectos	Si / No	+ / -
403	Cambio en el número de plagas de hongos, bacterias o virus	Si / No	+ / -
404	Cambio en el porcentaje de mortalidad de los cultivos	Si / No	+ / -
405	Cambio en los patrones de crecimiento de los cultivos	Si / No	+ / -
406	Cambio en los periodos de germinación, floración y maduración de los cultivos	Si / No	Antes/después
407	Cambio en la cota altitudinal favorable para cada cultivo **(Anotar cultivo)**	Si / No	Cota:
408	Cambio en el porcentaje de materia orgánica del suelo	Si / No	+ / -
409	**Ganadería**----Cambio en la cantidad de producción por cabeza de ganado	Si / No	+ / -

410	Cambio en la calidad de las materias primas de la ganadería	Si / No	+ / -
411	Cambio en la aparición de enfermedades en el ganado	Si / No	+ / -
412	Cambio en el comportamiento del ganado. Comportamiento inusual	Si / No	+ / -
413	Cambio en la distribución altitudinal del ganado extensivo en la sierra. Se suben solas.	Si / No	Cota:
414	Cambio en la disponibilidad de pastos a lo largo del año	Si / No	+ / -
415	Cambio en la calidad de los pastos	Si / No	+ / -
416	Cambio en la cantidad de aporte de pienso extra para el ganado.	Si / No	+ / -
417	**Apicultura**----Cambio en la producción de cada colmena	Si / No	+ / -
418	Cambio en el número de colmenas silvestres	Si / No	+ / -
419	Cambio en la aparición de depredadores y parásitos en las abejas	Si / No	+ / -
420	Cambio en el porcentaje de abejas muertas en cada colmena	Si / No	+ / -
421	Aparición de mutaciones o deformaciones en las abejas	Si / No	+ / -
422	Cambio en la época de enjambre y cría de las abejas	Si / No	Antes / después
423	**Silvicultura**----Cambio en la presencia de especies de árboles de ribera	Si / No	+ / -
424	Cambio en el número de fuegos	Si / No	+ / -
425	Cambio en la abundancia de productos del bosque: frutos silvestres, setas, espárrago	Si / No	+ / -
426	Cambio en la calidad de los productos del bosque	Si / No	+ / -
427	Cambio en la fecha de aparición(setas), floración y maduración de los frutos del bosque	Si / No	Antes / después

2. De todos los cambios de los que hemos hablado ¿Cuáles son los **cinco** que más repercuten en su estilo de vida? ¿Me podría dar un ejemplo concreto? ¿Le afectan de forma positiva o negativa? ¿Desde hace cuánto tiempo le afectan? Y ¿Cual es, según su opinión, el motivo que lo ha generado?

Cambio	*Ejemplo concreto y lugar de la observación*	+/-	*Fecha*	*Motivo*
1.				
2.				
3.				
4.				
5.				

3. ¿Ha oído hablar del Cambio Climático? SI / NO **4.** ¿Qué entiende usted por cambio climático?
....
....

5. Por lo que usted ha visto en Sierra Nevada ¿Considera que el cambio climático está afectando a Sierra Nevada? SI / NO.

6. Considera que el cambio climático es un problema importante para su vida diaria? SI / NO

7. Puntúe del 0 al 10 las siguientes amenazas a su sector (O= nada importante hasta 10= extremadamente importante)
(Preguntar sólo en caso de que la persona encuestada se dedique al sector primario)

- Éxodo rural y relevo generacional	0 1 2 3 4 5 6 7 8 9 10
- Sobreexplotación de los recursos naturales	0 1 2 3 4 5 6 7 8 9 10
- Cambio Climático	0 1 2 3 4 5 6 7 8 9 10
- Contaminación del medio, exceso de pesticidas y fertilizantes	0 1 2 3 4 5 6 7 8 9 10
- Competencia de precios en los mercados	0 1 2 3 4 5 6 7 8 9 10
- Cambio de uso del suelo	0 1 2 3 4 5 6 7 8 9 10

8. Si pudiera dejar al margen las repercusiones económicas de los impactos que hemos estado comentando. ¿Qué sentimientos le evocan a usted los cambios y las transformaciones que se están produciendo en Sierra Nevada? ……………………………………………………
……
……
……
……

A. ¿Ha variado su vida de algún modo con algún otro cambio de los que hemos comentado?……………………………………………
……
……

B. ¿Comenta con alguien los impactos percibidos del cambio climático a la hora de buscar medidas de adaptación? (Puede marcar más de uno)

☐ Familia ☐ Amigos/compañeros del sector

☐ Reuniones de cooperativas / asociaciones del sector ☐ Administración

☐ Otros ……………………………

C. ¿Estaría dispuesto a colaborar con la comunidad científica ayudándoles a identificar los principales cambios e impactos que ustedes están percibiendo en el terreno para mejorar su compresión? SI / NO

Participación CONECT-e

Próximamente se abrirá al público una plataforma on-line donde las personas que tengan una estrecha relación con el campo podrán contribuir con sus observaciones sobre los cambios que están percibiendo en su zona en relación con el cambio climático como acabamos de hacer en la encuesta. ¿Podría usar la información que me acaba de proporcionar sobre los cambios percibidos por usted para incluirla en la plataforma como una observación hecha por un usuario para contribuir al desarrollo de la plataforma? SI / NO ¿Podría volver a contactar con usted cuando esté abierta la plataforma para que participe en ella? SI / NO . Forma de contacto ……………………………………

Annex II.

Other publications related to the thesis

Publications directly related to the thesis

- Reyes-García, V., **García-del-Amo, D.**, Benyei, P., Fernández-Llamazares, Á., Gravani, K., Junqueira, A.B., Labeyrie, V., Li, X., Matias, D.M., McAlvay, A. and Mortyn, P.G., 2019. A collaborative approach to bring insights from local observations of climate change impacts into global climate change research. *Current opinion in environmental sustainability*, *39*, pp.1-8. https://doi.org/10.1016/j.cosust.2019.04.007.

- Garteizgogeascoa, M., **García-del-Amo, D.** and Reyes-García, V., 2020. Using proverbs to study local perceptions of climate change: a case study in Sierra Nevada (Spain). *Regional Environmental Change*, *20*, pp.1-12. https://doi.org/10.1007/s10113-020-01646-1

Publications related to the framework of the thesis

- Reyes-García, V., Fernández-Llamazares, Á., **García-del-Amo, D**. and Cabeza, M., 2020. Operationalizing local ecological knowledge in climate change research: Challenges and opportunities of citizen science. In *Changing climate, changing worlds* (pp. 183-197). Springer, Cham. https://doi.org/10.1007/978-3-030-37312-2_9

- Reyes-García, V., Fernández-Llamazares, A., Aumeeruddy-Thomas, Y., Benyei, P., Bussmann, R.W., Diamond, S.K., **García-del-Amo, D.**, Guadilla-Sáez, S., Hanazaki, N., Kosoy, N. and Lavides, M., 2021. Recognizing Indigenous peoples' and local communities' rights and agency in the post-2020 Biodiversity Agenda. *Ambio*, pp.1-9. https://doi.org/10.1007/s13280-021-01561-7

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ScienceDirect

Current Opinion in Environmental Sustainability

A collaborative approach to bring insights from local observations of climate change impacts into global climate change research

Victoria Reyes-García[1,2], David García-del-Amo[2], Petra Benyei[2], Álvaro Fernández-Llamazares[3,4], Konstantina Gravani[2], André B Junqueira[2], Vanesse Labeyrie[5,6], Xiaoyue Li[2], Denise MS Matias[2,7], Alex McAlvay[8,9], Peter Graham Mortyn[2,10], Anna Porcuna-Ferrer[2], Anna Schlingmann[2] and Ramin Soleymani-Fard[2]

Bringing insights from Indigenous and local knowledge into climate change research requires addressing the transferability, integration, and scalability of this knowledge. Using a review of research on place-based observations of climate change impacts, we explore ways to address these challenges. Our search mostly captured scientist-led qualitative research, which – while facilitating place-based knowledge transferability to global research – did not include locally led efforts documenting climate change impacts. We classified and organized qualitative multi-site place-based information into a hierarchical system that fosters dialogue with global research, providing an enriched picture of climate change impacts on local social-ecological systems. A network coordinating the scalability of place-based research on climate change impacts is needed to bring Indigenous and local knowledge into global research and policy agendas.

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Introduction

There is overwhelming evidence that climate change has not only direct effects on the climatic system, but also a discernible influence on physical and biological systems [1–3], with resulting impacts on local livelihoods and cultures [4]. Most of this evidence comes from research in the natural sciences relying on large-scale weather records and the use of modelling techniques to describe impacts in data deficient regions [5]. While such a research has advanced our understanding of climate change's global magnitude, its methods are too coarse to detect impacts on local social-ecological systems [6] for which scientists have called for exploration of locally grounded data sources [3].

Indigenous and Local Knowledge (ILK) has an untapped potential to contribute to research on climate change impacts on local social-ecological systems [7••,8••]. Indigenous Peoples and Local Communities (IPLC) with a history of interaction with the environment have

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ORIGINAL ARTICLE

Using proverbs to study local perceptions of climate change: a case study in Sierra Nevada (Spain)

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Abstract

Local communities' dependence on the environment for their livelihood has guided the development of indicators of local weather and climate variability. These indicators are encoded in different forms of oral knowledge. We explore whether people recognize and perceive as accurate one type of such forms of oral knowledge, climate-related proverbs. We conducted research in the Alta Alpujarra Occidental, Sierra Nevada, Spain. We collected locally recognized proverbs and classified them according to whether they referred to the climatic, the physical, or the biological system. We then conducted questionnaires ($n = 97$) to assess informant's ability to recognize a selection of 30 locally relevant proverbs and their perception of the accuracy of the proverb. Climate-related proverbs are abundant and relatively well recognized even though informants consider that many proverbs are not accurate nowadays. Although proverbs' perceived accuracy varied across informant's age, level of schooling, and area of residence, overall proverb's lack of reported accuracy goes in line with climate change trends documented by scientists working in the area. While our findings are limited to a handful of proverbs, they suggest that the identification of mismatches and discrepancies between people's reports of proverb (lack of) accuracy and scientific assessments could be used to guide future research on climate change impacts.

Keywords Andalucía (Spain) · Climate change impacts · Ethnoclimatology · Indigenous and local knowledge · Proverbs

Introduction

In their quest to better understand local climate change impacts, both natural and social scientists are challenged by the scarcity of grounded data. This has resulted in climate scientists calling for the exploration of new data sources (Rosenzweig and Neofotis 2013). Within this context, several authors have argued that local ecological knowledge has an untapped potential to contribute to further our understanding of local climate change impacts (Barnes et al. 2013; Savo et al. 2016). Researchers have documented many instances in which Indigenous peoples or local communities with a long history of interaction with the environment have developed complex knowledge systems that allow them to detect changes in local weather and climatic variability, as well as the impacts of such changes in the physical and the biological systems on which they depend (e.g., Orlove et al. 2000; Fernández-Llamazares et al. 2015; Reyes-García et al. 2016). Through observations of their immediate environment accumulated over generations and continuously adapted to environmental and other changes, local populations have developed a large body of ethnoclimatological knowledge, defined as "the comprehensive system of insights, experiences, and practices regarding climate and local weather events, as well as their changes at different spatiotemporal scales" (Reyes-García et al. 2018).

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Chapter 9
Operationalizing Local Ecological Knowledge in Climate Change Research: Challenges and Opportunities of Citizen Science

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Abstract Current research on the local impacts of climate change is based on contrasting results from the simulation of historical trends in climatic variables produced with global models against climate data from independent observations. To date, these observations have mostly consisted of weather data from standardized meteorological stations. Given that the spatial distribution of weather stations is patchy, climate scientists have called for the exploration of new data sources. Knowledge developed by Indigenous Peoples and local communities with a long history of interaction with their environment has been proposed as a data source with untapped potential to contribute to our understanding of the local impacts of climate change. In this chapter, we discuss an approach that aims to bring insights from local knowledge systems to climate change research. First, we present a number of theoretical arguments that give support to the idea that local knowledge systems can contribute in original ways to the endeavors of climate change research. Then, we explore the potential of using information and communication technologies to gather and share local knowledge of climate change impacts. We do so

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KUNGL. VETENSKAPS-AKADEMIEN
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PERSPECTIVE

Recognizing Indigenous peoples' and local communities' rights and agency in the post-2020 Biodiversity Agenda

Victoria Reyes-García, Álvaro Fernández-Llamazares, Yildiz Aumeeruddy-Thomas, Petra Benyei, Rainer W. Bussmann, Sara K. Diamond, David García-del-Amo, Sara Guadilla-Sáez, Natalia Hanazaki, Nicolas Kosoy, Margarita Lavides, Ana C. Luz, Pamela McElwee, Vicky J. Meretsky, Teresa Newberry, Zsolt Molnár, Isabel Ruiz-Mallén, Matthieu Salpeteur, Felice S. Wyndham, Francisco Zorondo-Rodriguez, Eduardo S. Brondizio

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Abstract The Convention on Biological Diversity is defining the goals that will frame future global biodiversity policy in a context of rapid biodiversity decline and under pressure to make transformative change. Drawing on the work of Indigenous and non-Indigenous scholars, we argue that transformative change requires the foregrounding of Indigenous peoples' and local communities' rights and agency in biodiversity policy. We support this argument with four key points. First, Indigenous peoples and local communities hold knowledge essential for setting realistic and effective biodiversity targets that simultaneously improve local livelihoods. Second, Indigenous peoples' conceptualizations of nature sustain and manifest CBD's 2050 vision of "Living in harmony with nature." Third, Indigenous peoples' and local communities' participation in biodiversity policy contributes to the recognition of human and Indigenous peoples' rights. And fourth, engagement in biodiversity policy is essential for Indigenous peoples and local communities to be able to exercise their recognized rights to territories and resources.

Keywords Biodiversity policy · Convention on Biological Diversity · Indigenous and local knowledge · Nature's values · Right-based approach

INTRODUCTION

The Convention on Biological Diversity (CBD) is now working to formulate the goals that will frame global biodiversity policy for decades to come. The Parties to the Convention are doing so while facing the fact that they failed to achieve most of the targets of the 2011–2020 Strategic Plan for Biodiversity while global biodiversity continues to decline precipitously (Green et al. 2019). Moreover, the window of opportunity to take action is narrowing (Díaz et al. 2019; IPBES 2019a, b). To slow biodiversity loss, transformative change, i.e., a fundamental system-wide reorganization, is needed in the ways biodiversity policies are designed, implemented, and enforced, from international to national scales, and across sectors (Díaz et al. 2020).

In this 'Perspective', we argue that transformative change requires the foregrounding of Indigenous peoples and local communities' (IPLC) rights and agency in biodiversity policy. Much of the world's biodiversity now exists in landscapes and seascapes traditionally owned, managed, used and/or occupied by IPLC (Brondizio and Le Tourneau 2016; Garnett et al. 2018). Moreover, despite increasing resource extraction pressures (Díaz et al. 2019) and growing violence against IPLC who are defending their territories and resources (Scheidel et al. 2020), biodiversity is declining more slowly in areas managed by IPLC than elsewhere (Garnett et al. 2018; Fa et al. 2020; O'Bryan et al. 2020).

However, IPLC continue to face challenges to full participation in the crafting and implementation of biodiversity policy at local, regional, and global levels (Witter et al. 2015; Forest Peoples Programme et al. 2020). For example, while about 40% of terrestrial protected areas overlap with IPLC lands (Garnett et al. 2018), IPLC only formally govern < 1% of them (UNEP-WMCM et al. 2018). Further, the current zero draft of the post-2020 biodiversity framework continues to make the same long-standing calls for promotion of traditional knowledge and "full and effective participation" of IPLCs without the more concrete measures they have requested (see Box).

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