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Review

Agroecology for adaptation to climate change and resource depletion in the Mediterranean region. A review

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ABSTRACT

Mediterranean agriculture has coevolved with harsh environments and changing climate conditions over millennia, generating an extremely rich heritage of traditional knowledge; however, it is particularly threatened by climate change, including a higher than average warming and more frequent extreme climate events. The vulnerability is enhanced by the other components of global change affecting the Mediterranean basin, including biodiversity loss, freshwater overuse, disrupted nutrient cycles, soil degradation and altered fire regimes, in a context of high population density, water scarcity, high dependence on biomass and energy imports, and the prevalence of highly specialized, low diversity agroecosystems. Due to the need to create resilience to these interconnected threats, systemic adaptation measures are urgently needed. This review shows that this systemic approach can be provided by agroecology, which offers a holistic framework enabling the recovery and assessment of traditional knowledge and the cocreation of new local knowledge for enhancing resilience. It also highlights the role of the reconnection of food production and consumption, associated with the recovery of the locally-adapted, largely plant-based Mediterranean diet. Three types of complementary adaptation strategies for crop production are identified: (i) Biodiversity management to spread out risks and reduce pest damage; (ii) Increasing soil organic matter, e.g. with cover crops or crop varieties with higher residue and root production; (iii) Reducing fossil fuel dependence by avoiding synthetic chemicals, increasing efficiency and using renewable energy. Livestock adaptation strategies identified include: (i) management of extensive herds, including practices such as transhumance; (ii) diversification, use of local breeds and change of species; (iii) pasture and forage management, focusing on adjusting stocking rates to prevent abandonment and intensification, agroforestry, and fire management through grazing. Public policies must be set to tailor these strategies to each specific local situation with the involvement of all stakeholders and to establish or reinforce networks allowing knowledge exchange.

1. Introduction

Agriculture intrinsically depends on climatic conditions and, consequently, it is one of the most vulnerable sectors to the risks of global climate change (CC). The negative impacts of CC on agriculture may be amplified by non-linear interactions between the components of the climate system and by interactions with resource depletion and with other components of global change, such as land-system changes, freshwater use, nutrient cycles and biosphere integrity (Steffen et al., 2015). These connections between global change processes underline the need for integrated approaches to build food production systems that are not just climate-resilient, but also global change-resilient and resource depletion-resilient, particularly in the highly vulnerable Mediterranean basin (Cramer et al., 2018; Malek et al., 2018). The Mediterranean climate is characterized by mild, wet winters and hot, dry summers, but also by a large spectrum of high impact atmospheric processes, such as floods, droughts and cyclogenetic patterns (Michaelides et al., 2018). This climate type is localized in five areas around the world (Fig. 1). Most of its subtypes can be classified as semi-arid, and rainfed crops are usually exposed to water deficit conditions. Irrigation has a major role in Mediterranean agriculture, and is often proposed as a strategy to reduce the impacts of CC in semi-arid areas. However, irrigation has also been shown to have biophysical limits hampering its sustainability (Bird et al., 2016), including water and energy use, and greenhouse gas emissions (Aguilera et al., 2019a; Daccache et al., 2014).

The geographical distribution of expected effects of CC on agriculture is highly uneven (IPCC (Intergovernmental Panel on Climate Change), 2014). The Mediterranean basin is one of the regions in which these effects are going to be more negative for agriculture. For example, this region has been identified as a major hotspot for drought risk (Carrao et al., 2016), and it has been estimated that global warming

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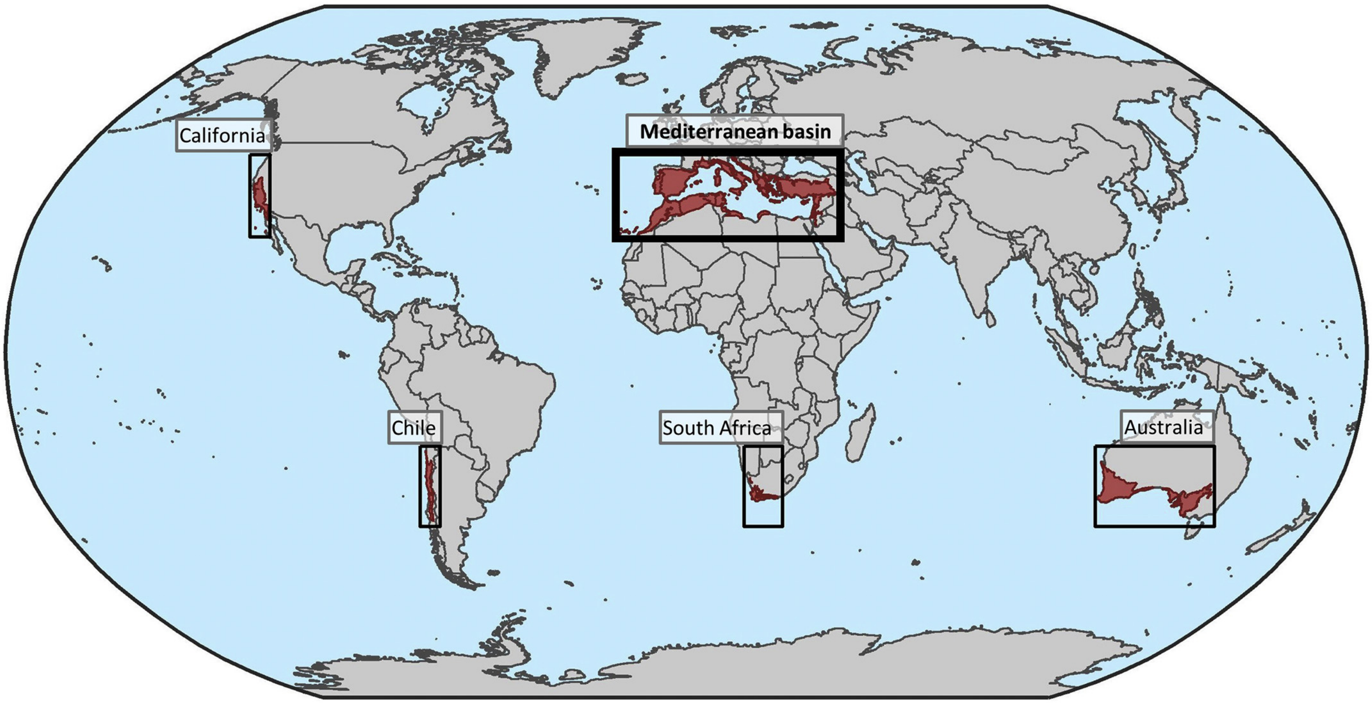

Fig. 1. Global distribution of the Mediterranean biome (marked in red), highlighting the Mediterranean basin among the five global regions with this type of climate. Based on the Global 200 assessment (Olson and Dinerstein, 2002)

above 1.5°C will drive Mediterranean ecosystems beyond Holocene variability (Guiot and Cramer, 2016). These impacts are in addition to other human-driven impacts on land, which are responsible for a high risk of land degradation in the Mediterranean basin (Lagacherie et al., 2018; Zalidis et al., 2002). The severe threats posed to Mediterranean agroecosystems by CC, along with the existence of a "Mediterraneization" process in many areas of the world (Hernandez et al., 2017), make the study of CC adaptation in these areas a top priority in agricultural research. Moreover, the Mediterranean basin has a high, growing population that is projected to reach 529 million by 2025 (GRID-Arendal, 2013), and its agriculture is strongly dependent on imported resources (Sanz-Cobena et al., 2017).

Adaptation is a key factor that will determine the future severity of the impacts of CC on agriculture and food production in the Mediterranean (Iglesias et al., 2010). Adaptation to changes in climate has been a continuous process throughout the millennial history of Mediterranean agriculture, with adaptive changes in farming practices being recorded since at least 12.9-11.5 ky B.P. (Rosen and Rivera-Collazo, 2012). The landscapes of the basin have coevolved with their environments and societies, resulting in an extreme diversity of agroecosystems with high ecological value (Blondel, 2006). This diversity is associated with the traditional ecological knowledge of Mediterranean farmers, which now constitutes a fundamental source of information (including genetic diversity) for coping with CC in modern Mediterranean agroecosystems. Yet, the conservation of this knowledge is jeopardized by rural abandonment, a major socio-environmental problem in many Mediterranean areas. For example, rural abandonment is increasing the vulnerability to CC through the increase in fire risk and through the loss of the biodiversity associated with traditional landscape mosaics.

Agroecological practices have been proposed as promising tools for CC adaptation (Altieri et al., 2015). The agroecological approach addresses the agro-environmental problems through a holistic perspective, which is necessary to tackle the multi-dimensional challenges of agriculture under global change (Lal, 2018). This holistic perspective not only considers the farm scale, but the food system as a whole, including environmental and socioeconomic aspects. Agroecological practices are now expanding in the Mediterranean basin, where they are contributing to the sustainability of agriculture (Migliorini et al., 2018), but the information on their contribution to CC adaptation is sparse in the literature.

The aim of this review is to synthetize the scientific information related to agroecological adaptation to CC and resource depletion in the Mediterranean region. Firstly, the major threats to agroecosystems are described, including impacts on natural and managed ecosystems, and energy, soil and water resources; then, the systemic approach proposed in this work for adaptation to CC and resource depletion is outlined, including a brief description of agroecological adaptation, a discussion on the role of traditional knowledge and knowledge cocreation, and an overview of the role of the Mediterranean diet in the territorial reconnection of production and consumption; lastly, the Mediterranean-specific research on agroecological adaptation to CC and resource depletion at the farm scale is described, not aiming to comprehensively review all agroecological practices but rather to focus on some representative strategies in crop and livestock production.

2. Impacts of climate change and resource depletion in the Mediterranean basin

2.1. Climatic trends and impacts on natural and semi-natural ecosystems

Climate projections show that the arid climate type is likely to expand into Euro-Mediterranean areas during the 21st century, while the Mediterranean climate would expand northward into Central and Eastern Europe (Alessandri et al., 2014). The average increase in temperature in the 21st century is expected to be 20% higher than the world average, while precipitation is expected to decrease by around 20 mm/°K (Lionello and Scarascia, 2018), and droughts are expected to be more frequent, long and severe, even under a high GHG mitigation scenario (Grillakis, 2019). The changes are already being noticed. In recent decades, Europe, and particularly the Mediterranean basin, has shown an increase in the interannual variability in precipitation and temperature, as well as in extreme climatic events (Brilli et al., 2014), while most of the Mediterranean regions in the world have experienced a decrease in net primary productivity in the period 2000-2009 (Potter et al., 2012). There is increasing evidence that these changes in climatic patterns are already altering terrestrial ecosystems in the Mediterranean region, including changes in genes, individuals and communities, as well as increased fire risk and reduced C and nutrient uptake capacity (Penuelas et al., 2018). The impacts of CC on Mediterranean ecosystems interact with other global change factors such as changes in atmospheric composition and land use intensification and abandonment (Doblas-Miranda et al., 2017). Abandonment commonly occurs in association with intensification, driven by a combination of social, economic, geographical and demographical factors (Debolini et al., 2018). Mediterranean ecosystems are usually fire-prone and their species are adapted to fire occurrence, with many of them actually benefiting from fire for their survival and dispersion (Cross et al., 2017; Lawson et al., 2010). Nonetheless, the changes in fire regimes are particularly worrisome in the present. The projected increase in burned area in the European Mediterranean region ranges from 40%–100% for global warming scenarios ranging from 1.5–3°C (Turco et al., 2018). The main driver is probably the expansion of large continuous forest areas with high fuel loads and flammability, which are now widespread due to rural abandonment, expansion of coniferous plantations, and application of fire suppression strategies for conservation purposes, which reduce burned areas in the short term but boost the risk of large fires in the long term (Curt and Frejaville, 2018; Fernandes, 2013), and also the risk of these large fires clustering disastrous mega-fires (San-Miguel-Ayanz et al., 2013). Paradoxically, therefore, rural abandonment can eventually lead to a net deforestation, thus reversing the forest transition, as has been recently observed in Portugal (Oliveira et al., 2017). Other global change factors such as urban sprawl also increase fire hazard and the impacts on the economy and human lives posed by fires (Fox et al., 2018; Moreira et al., 2011). The combination of all these factors with changes in climate patterns creates a “perfect storm” that severely threatens natural ecosystems and human lives. Moreover, the increase in fire recurrence in Mediterranean areas can lead to transitions to fire-prone shrublands, which is associated with declines of soil organic carbon (SOC) and soil fertility in the long term (Mayor et al., 2016; Moreira et al., 2011).

2.2. Resource depletion and deterioration. Energy, water and soils

Energy, water and soils are essential resources for agriculture. In the Mediterranean basin, the impacts of CC, global change and the direct anthropogenic pressure are severely threatening the provision of these resources.

Peak fossil fuels, declining energy returns on investment (EROI) of fossil fuels (Court and Fizaine, 2017) and low EROIs of low carbon solutions (King and van den Bergh, 2018) will have profound socioeconomic implications. Given the high reliance of modern agriculture on external energy inputs (Gingrich et al., 2018), these negative impacts could also be expected for agriculture, harming food security and equity (Neff et al., 2011). In the Mediterranean basin, there is high dependence on non-renewable and imported energy (Fig. 2a). Only four countries (Algeria, Libya, Egypt and Syria) produce significant amounts of fossil fuels, but production in all of them is declining. On the other hand, the share of renewable energy has increased during the 21st century (Fig. 2b), but it is still very low, just 11% of total primary energy consumption (less than 4% in Southern countries). Therefore, Mediterranean countries are highly dependent on fossil fuels in a context of declining production, putting them in a vulnerable situation.

This vulnerability also affects their agricultural systems, which are highly reliant on non-renewable energy (Alonso and Guzmán, 2010). More than 0.5 units of non-renewable energy, including fossil fuels and nuclear energy, are currently used to produce each average crop energy unit (Fig. 3). This value has roughly doubled from 1961 to 2012. Non-renewable energy intensity of crop production is slowly declining in North Mediterranean countries, but it is growing fast in East and South Mediterranean countries. Electricity, which is used for irrigation, is the item that is growing most, which underlines the fact that the availabilities of the different resources are closely interlinked. In the Mediterranean basin, where water deficit situations are widespread, and irrigation multiplies yields, high energy investments are being made to provide irrigation at the cost of a high dependence on non-renewable and carbon intensive energy sources.

Water is a scarce resource in the Mediterranean basin, not just in absolute terms but also as a result of the temporal concentration of precipitation and the high inter-annual variability with the presence of frequent droughts (Fader et al., 2016). Currently, the observed climatic trends are aggravating the water shortage in the Mediterranean basin. Many countries have experienced water shortages during the last 20 years (Milano et al., 2013). Climate trends are expected to exacerbate this situation by increasing water demand, including higher water requirements for irrigation (Dono et al., 2016; Fader et al., 2016), in an area where agriculture is the largest consumer of fresh water (Nguyen et al., 2016). Another important impact is on the availability of groundwater, which is expected to be diminished by lower recharge rates (Green et al., 2011) and is particularly threatened in coastal areas, where sea level rise and soil subsidence may enhance sea water intrusion (Geriesh et al., 2015) and there can be a strong pressure from human activities (Jimenez-Martinez et al., 2016).

Soils in Mediterranean climate have typically low SOC levels (Chiti et al., 2012), and there is an abundance of shallow soils, salinization problems in irrigated areas, and a high spatial complexity in soil characteristics (Lagacherie et al., 2018). There is a widespread soil degradation (Lahmar and Ruellan, 2007), which is expected to be exacerbated by CC in the coming decades (Al-Adamat et al., 2007). For example, in Mediterranean Europe, the climate change-driven increase in rainfall aggressiveness is boosting the risk of desertification and land degradation (Diodato et al., 2011). These processes are reinforced by the negative impact of some agricultural practices on SOC, which interact with climatic factors (Aguilera et al., 2018; Zalidis et al., 2002). Moreover, Mediterranean soils are also threatened by other processes intensified by CC, such as soil erosion, pesticide or heavy metal pollution, or changes derived from shifts in plant species distribution. For example, the vulnerability to pesticide pollution is expected to increase due to alteration of pesticide adsorption and runoff caused by CC (Anaya-Romero et al., 2015). These trends interact in a non-linear way to reinforce the negative impacts of CC, diminishing the adaptive capacity of agroecosystems (Webb et al., 2017), which highlights the need for urgent changes in management practices.

2.3. Climate impacts on agroecosystems

CC impacts interact with those of resource depletion and other global change processes to jeopardize crop and livestock production in the Mediterranean Basin through multiple mechanisms (Fig. 4). The asynchrony between maximum temperature (and irradiation) and maximum precipitation is responsible for a typically low productivity in Mediterranean rainfed systems. In this context, CC scenarios project a more adverse effect on average crop yields in Mediterranean than in temperate zones (Knox et al., 2016). Likewise, stronger impacts are expected in the Southern areas of the Mediterranean basin, which contribute less to CC given their lower per capita GHG emissions (BP, 2018). These differences between where the worst impacts occur and where the responsibility for the present situation is held highlight the ethical dimension of mitigation and adaptation strategies to CC (Grasso and Feola, 2012). The vulnerability to CC in the Middle East and Northern Africa region is particularly severe (Waha et al., 2017), as agriculture represents the largest source of employment in many countries and population may double by 2070, increasing the pressure on water and land resources in an unstable political environment. Moreover, these inequalities are not only geographical, but they also occur within each territory. For example, Ponti et al. (2014) found

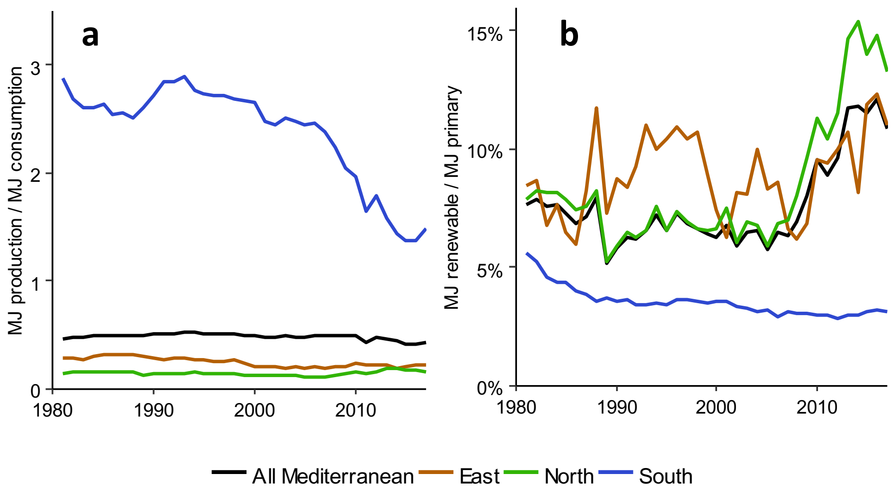

Fig. 2. Energy production and consumption (a), and share of renewable energy in their consumption mix (b) in Mediterranean countries, grouped by their location: all Mediterranean countries studied, Eastern countries (Cyprus, Lebanon, Israel and Turkey), Northern countries (France, Greece, Italy, Malta, Portugal and Spain) and Southern countries (Algeria, Egypt, Morocco and Tunisia). Own elaboration with data from BP (2018) and EIA (https://www.indexmundi.com/energy/).

greater vulnerability of small producers in marginal areas to increases in infestations of the olive fruit fly (*Bactrocera oleae*) driven by CC in the Mediterranean basin.

In the absence of adaptation measures, cereal yields are projected to decrease in Mediterranean areas due to temperature-driven phenological shifts including shortening the period of grain filling (Bird et al., 2016). For example, a modeling study (Saadi et al., 2015) shows that wheat yields in the Northern Mediterranean (except Turkey) could decrease up to 50% for most locations, while this reduction could reach 95% in Southern and Eastern regions. CC models also predict a reduction in the production of many horticultural crops (Bird et al., 2016; Saadi et al., 2015), and a negative impact of extreme precipitation events has already been observed (Diacono et al., 2016). Woody crops (olive, vine, fruit trees, etc.) are affected by extreme weather events such as hail and storms which can reduce or completely destroy the harvest (Olesen and Bindi, 2002). Modeling studies show a climate-driven decrease in the productivity of typical Mediterranean woody crops such as vineyards and olives, as well as the displacement of their cultivated area to the North of the basin (Lionello et al., 2014; Moriondo et al., 2013). Some models predict an advance of olive (Orlandi et al., 2010) and vineyard (Ramos, 2017) phenological stages, reinforcing the patterns observed in recent years.

Climate influences most of the critical factors for livestock production, since it determines the availability of pastures and feed and has direct effects on animal health (proliferation of pests and pathogens), growth and reproduction and water requirements (Rojas-Downing

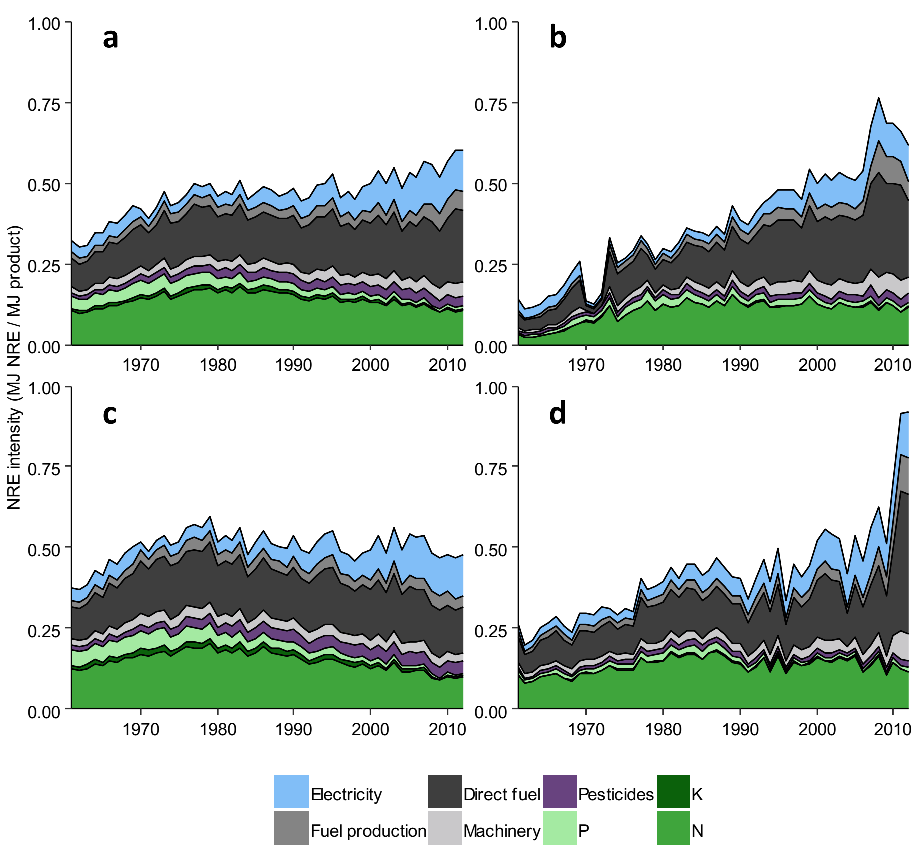

Fig. 3. Non-renewable energy intensity of crop production in Mediterranean countries, grouped by their location: (a) all Mediterranean countries studied, (b) Eastern countries (Cyprus, Lebanon, Israel and Turkey), (c) Northern countries (France, Greece, Italy, Malta, Portugal and Spain) and (d) Southern countries (Algeria, Egypt, Morocco and Tunisia). Own elaboration, see Supplementary Information.

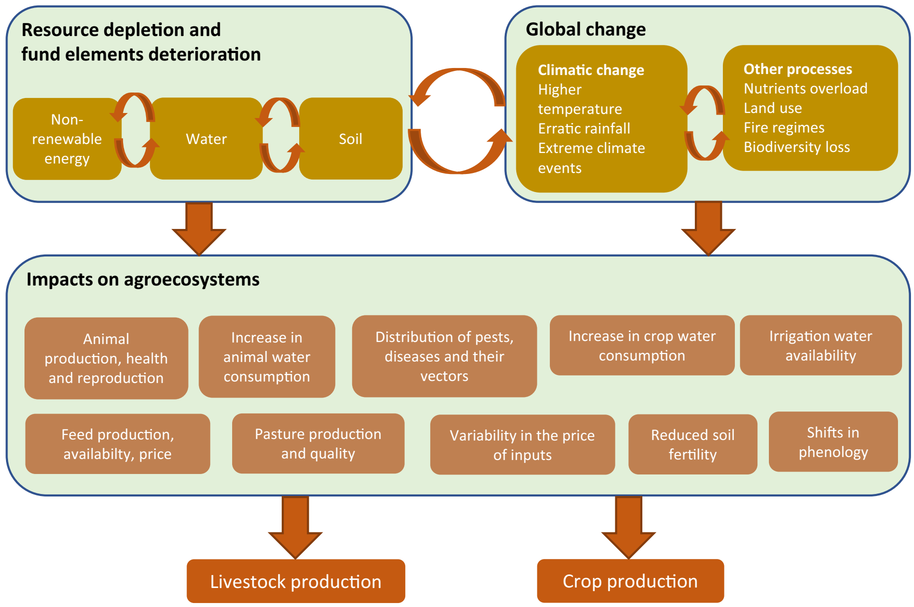

Fig. 4. Simplified representation of major impacts of resource depletion, climate change, and other global change processes on Mediterranean agroecosystems.

et al., 2017). Some of the main impacts on Mediterranean environments are summarized in Fig. 4. Thermal stress causes the loss of appetite of the animals, reducing their growth and the quality of production, increasing costs, and hampering animal welfare. Consequently, the current trends of increasing temperatures and more frequent and severe droughts are negatively affecting livestock productivity in Mediterranean regions of Europe, affecting most species, e.g. ruminants, such as dairy sheep (Finocchiaro et al., 2005), but also less studied livestock types, such as bees (Flores et al., 2019). Rivera-Ferre et al. (2016) identify three types of livestock systems with specific challenges related to CC: grazing systems, mixed crop-livestock systems and industrial systems. Extensive systems include grazing systems and many mixed systems, and they can be defined as those in which animals obtain most of their food resources from the local environment, mostly from grazing, and are located in low productivity areas. They share threats related to local climate impacts, while the impacts on industrial systems are mainly related to their global supply chains (Rivera-Ferre et al., 2016). Extensive livestock production systems have shaped traditional landscapes in the Mediterranean basin, interacting with natural heterogeneity to create the wide diversity of habitats in this region (Sal, 2000). It has been estimated that complex agro-sylvo-pastoral mosaics still cover 23.3% of the Mediterranean ecoregion (Malek and Verburg, 2017). One of the main challenges of Mediterranean extensive livestock systems is their low profitability, which leads to intensification and abandonment processes (Acha and Newing, 2015; Godinho et al., 2016). Although both processes coexist in the same territory, intensification prevails in Southern Mediterranean areas, while abandonment prevails in Northern Mediterranean ones (Bugalho et al., 2011). Both processes result in the loss of the traditional multi-functionality of these systems and in their ability to provide valuable ecosystem services, making them more vulnerable to disturbances such as fires, droughts and diseases, whose frequency and intensity is increasing. Intensification causes a lack of natural regeneration and tree death in over-aged stands affecting the ecological stability and sustainability of the whole system (Herguido et al., 2017; Moreno and Pulido, 2009). Likewise, intensification reduced oak recruitment in sylvo-pastoral oak woodlands of Lesvos island in Greece, which could trigger a feedback cycle with increasing drought (Plieninger et al., 2011). These negative intensification processes are partly driven by inappropriate policies applying criteria developed in temperate areas to Mediterranean ones. For example, some national and European policies (EC (European Commission, 1991, 2009)), have been misused to establish stocking rate limits of extensive livestock in Mediterranean areas that are much higher than the sustainable stocking rates (Díaz-Gaona et al., 2014b).

3. Agroecology as a systemic approach to climate change adaptation

3.1. Conceptualizing agro-ecological adaptation in the Mediterranean

Agroecology proposes a holistic approach to agricultural sustainability, based on the participatory interaction between traditional knowledge and modern science, in order not only to reduce environmental impacts but also to serve the socio-economic needs of farmers and the society (Altieri, 1989). Beyond technological changes, agroecology underlines the need for the political reinforcement of rural communities, the increase in equity, both internal (i.e. gender equality) and external (with other sectors of the agri-food system), and the development of local agri-food systems, more fair and accessible to farmers and low-income consumers (Méndez et al., 2015). Those aims have led to the development of Political Agroecology as a tool to promote the required institutional and legislative changes (González de Molina et al., 2019). This broad vision, including a focus on the whole food system beyond agricultural production, rethinking the prevailing economic paradigm and deepening democracy, distinguishes agroecology from other climate-related proposals such as climate-smart agriculture (Pimbert, 2015).

The fact that agroecology articulates agronomic and ecological aspects with socio-economic, cultural and political aspects has promoted its conceptualization to occur in regions with a high cultural and socio-political integration. That is the case of the construction of the agroecology concept in Latin America (Gliessman, 2017) or the more recently taking place in Europe (Gallardo-López et al., 2018). In the European countries of the Mediterranean basin, agroecology is emerging as a concept encompassing a wide array of locally-adapted practices that contribute to the sustainability of Mediterranean cropping systems (Migliorini et al., 2018). However, the generation of a common agroecology concept has not taken place in the Mediterranean Basin as a whole, probably due to the socioeconomic and cultural differences, and the political barriers between Northern and Southern countries of the basin. The common agroecological features, however, suggest that important synergies may arise from a conceptual and strategical approach to agroecology in both shores of the Mediterranean sea, which could be key to face the challenges posed by climate change, resource depletion and other global change processes.

Certified organic farming systems ensure the application of some agroecological principles by banning synthetic pesticides and fertilizers and enforcing high animal welfare standards (EC (European Commission), 1991, 2018). However, from an agroecological perspective, some authors have warned about the “conventionalization” of organic farming (Darnhofer et al., 2010b), a process that has been recorded in Mediterranean areas such as Andalusia (Ramos García et al., 2018). For example, organic regulations allow the existence of monoculture farming, which barely contributes to agroecosystem resilience. Furthermore, the integration of the organic sector in conventional processing and marketing structures undermines the economic viability of organic farms, their potential for rural development, and the access of the population to organic products (Navarrete, 2009). Even so, the clear regulation of organic farming systems facilitates comparisons with conventional ones, and therefore they are taken in this review as examples (even if limited) of the possible outcomes that could be achieved by applying agroecological principles.

Agroecological systems are able to maintain productivity with a low use of external inputs by relying on internal ecological processes such as organic matter recycling, the functional diversification of crops and the agro-sylvo-pastoral integration. This implies a profound difference with industrial systems in the energy metabolic pattern, with agroecological systems showing a greater share of energy temporally stored in internal loops (Guzmán and González de Molina, 2017), which shape the configuration of agricultural landscapes into mosaics of heterogeneous land cover patterns. These mosaics provide ecosystem services such as biodiversity conservation (Marull et al., 2019), and they have been shown to enhance multitrophic diversity more than the amount of seminatural cover in the landscape (Sirami et al., 2019). These facts potentially confer agroecological systems less vulnerability to changes in external conditions (Brzezina et al., 2016). A recent meta-analysis has not found an effect of organic management on yield variability (Lesur-Dumoulin et al., 2017), but reduced yield variability of specific crops is probably less important as a source of resilience than system diversification, which allows shifting activities under a changing environment and thus coping better with harsher situations, as has been shown in Tunisian farming systems (Souissi et al., 2018). It is precisely the combination of strategies that makes agro-ecological solutions effective for responding to extreme events (Altieri et al., 2015; Diacono et al., 2016; Mijatović et al., 2013).

The focus of agroecology on the social dimension of sustainability, in relation to adaptation potential and resilience building in the Mediterranean basin, implies reinforcing a renovated and diverse farming population. In particular, given the present ageing and male-dominant rural population, Recanati et al. (2019) identified four social groups that should be strengthened to achieve resilient rural communities in Europe: (i) young farmers; (ii) new entrants; (iii) small-scale farmers; (iv) women farmers. We would add “immigrant farm workers and farmers”. After decades of emigration from European Mediterranean countries to Central and Northern Europe and from rural to urban areas, immigrants arriving in Mediterranean Europe from Southern Mediterranean countries are helping reverse the rural abandonment problem in many areas (Kasimis et al., 2003). Beyond these clear benefits, these immigrants represent a de facto connection between Southern and Northern Mediterranean agricultures, with an untapped potential to generate useful knowledge and adaptive networking across the Mediterranean. The development of this potential would require the creation of mechanisms for knowledge exchange but also the improvement of labour and life conditions of the immigrants. For example, immigrants in intensive vegetable and fruit producing areas of Spain and Italy are often in an illegal situation or facing social exclusion, and are also highly vulnerable to economic crises (Checa Olmos et al., 2018; Hoggart and Mendoza, 1999).

3.2. Recovering traditional knowledge and coproducing local knowledge

Behind the wide diversity of traditional farming systems, many of them share common agroecological features that are interesting in a context of CC, such as a high animal and plant diversity, high structural diversity, exploitation of a range of microclimates, or dependence on local resources and crop varieties (Altieri and Nicholls, 2017). The long agricultural history of the Mediterranean basin can thus serve as a particularly rich source of genetic resources and management practices for CC adaptation.

There are many examples of the adaptive potential of traditional knowledge in the Mediterranean basin. Gómez-Baggethun et al. (2012) assessed adaptive practices in SW Spain from 1577 to 1956, concluding that traditional ecological knowledge contributed to the maintenance of long-term resilience and the collective response to crises through a wide array of practices, including forecasting, mobility, storage, rationing, selection, pooling and diversification. The Mediterranean basin has a long history developing soil and water conservation techniques (Lagacherie et al., 2018; Migliorini et al., 2018), including those based on slope correction (e.g. terracing), increasing the soil cover (e.g. cover crops, tree-herbaceous crop associations) and soil quality improvement (e.g. amendments). The case of terracing abandonment, very common in Mediterranean areas, is particularly worrisome because it triggers soil erosion and landslide risk, besides the loss of the cultural heritage and rural development potential (Ramos et al., 2007; Tarolli et al., 2014). Another example is the “pozas” (meaning “hollows”), an earthwork technique for efficient material and water trapping on the slope (Ballais et al., 2013). Another example of traditional knowledge applied to water conservation in the Mediterranean is the cultivation of species that usually have high water requirements under water-limited rainfed conditions. This is possible due to the use of adapted local varieties in combination with specific soil management practices, as in the case of tomato cultivation in Santorini (Migliorini et al., 2018). Appropriate design of polycultures (e.g. larger crops protect the more delicate ones) and the use of live barriers (eg: with corn, fruit trees or natural vegetation) to protect from the sun and winds are also common in traditional Mediterranean agroecosystems (Alonso Mielgo, 2000). Windbreaks in Mediterranean areas have been shown to decrease crop evapotranspiration (Campi et al., 2012), leading to measurable increases in crop yield at a distance of up to 18 times the windbreak height (Campi et al., 2009). We discuss some specific key features of the application of traditional knowledge to climate change adaptation in the crop (Section 4) and animal (Section 5) sections.

It is important to notice that traditional management practices also have to be assessed to ensure that they would be sustainable in each specific local context. For example, traditional shifting cultivation in Mediterranean mountains has been linked to soil degradation and low vegetation recovery (Lasanta et al., 2017). In addition, agroecosystems have to adapt continuously to new socio-environmental contexts, particularly in the present situation of global change. Therefore, beyond the need to recover traditional knowledge, there is a need to cocreate new local knowledge among the involved stakeholders, in order to effectively tackle agroecosystem complexity. This innovation should be based on the redesign of the existing systems in order to find the most sustainable solutions at the local level (Barbier and Elzen, 2012). In this context, Levidow et al. (2013) underline how innovation in agroecology is not just a research-driven approach based on scientific knowledge and developing capital-intensive technologies, but a process of networking and iterative learning among a heterogeneous set of actors, combining traditional, technical and scientific knowledge. Anderson et al. (2018) systematize this process of agroecological learning by stablishing four pillars: (i) “diálogo de saberes”, or dialogue between ways of knowing, including amongst food producers (with an emphasis on mobility), between farmers and other actors of the food system, and between farmers and mainstream research education; (ii) horizontal learning, positioning learners as subjects of their own learning processes and participants of the production of collective knowledge, rather than as the object of teaching; (iii) combining practical and political knowledge; (iv) building social movement networks. These participatory processes could greatly benefit from the inclusion of model simulations incorporating the traditional/empiric knowledge of farmers and advisors and the scientific knowledge of researchers, as has been shown for upscaling crop-livestock integration (Martin et al., 2016). In Southern France, farmers are testing agroecological practices in their own experiments, and a generic framework has been developed to improve experimentation tools and methods (Catalogna et al., 2018). At the European level, the Agroecology Knowledge Exchange Network (EAKEN), linked to the global network La Via Campesina, is explicitly developing agroecological learning as a method of social transformation (Anderson et al., 2018). From our point of view, these initiatives are very powerful tools for agricultural adaptation to CC in the Mediterranean region, so they should be specifically promoted by public policies. Similar initiatives, however, are needed in the Southern Mediterranean, where adaptation is most urgent. In addition, Northern and Southern agroecological learning initiatives should be integrated to facilitate knowledge exchange and capacity building across the whole Mediterranean region.

3.3. Upscaling agroecology. From farmers organization to the link between producers and consumers

Technical and management changes in agroecosystems have to be combined with major dietary changes and reductions in food waste in order to keep the agro-food system within planetary boundaries (Springmann et al., 2018). From a systemic perspective, crossing those boundaries not only means a failure of mitigation strategies, but also a major threat for adaptation. Therefore, an agroecological approach to CC adaptation cannot ignore the role of the post-harvest stages of the agri-food system and consumer behavior, which also shapes the demand for agricultural products and consequently the combinations of species that can be applied on the farm. In the industrial food system, national and supra-national policies and large distribution systems have promoted the specialization and biodiversity decline of farming systems (Rotz and Fraser, 2015). Contrastingly, there is a direct link between production and consumption in local food systems, resulting in diverse production systems. The importance of these links is also reflected in the difficulties of modern agro-food systems for recycling the nutrients and carbon extracted from the farm. On the one hand, global feed trade has created a global disconnection between crop and livestock production (Lassaletta et al., 2014a). On the other hand, the widespread use of synthetic chemicals contaminates urban organic waste with pollutants, hampering their safe use for food production (Ait-Mouheb et al., 2018). Post-harvest stages of modern food systems are also very energy intensive; for example, in Spain their energy use had increased by one order of magnitude since 1960 (Infante-Amate et al., 2018). Consequently, the agroecological literature has stressed the role of local food systems to achieve agricultural sustainability and resilience, for example, through reduced energy needs for transportation and packaging (Pérez-Neira and Grollmus-Venegas, 2018), but also by closing nutrient cycles and reducing nutrient surplus (Billen et al., 2019), by increasing the decision-making autonomy of individual farmers (Rotz and Fraser, 2015), by a better ability to deal with sudden market changes (King, 2008), and by facilitating coevolutionary processes (Saifi and Drake, 2008). A key issue is the development and reinforcement of local networks that increase the resilience of agrarian production, but also of the agri-food system as a whole. Some examples are the networks aimed to provide the necessary farm inputs, such as seed exchange networks, or those exchanging manure for access to pasturelands or to crop residues for grazing. In Italy, the organization of farmers in agricultural cooperatives have been linked to the reinforcement of local supply chains and to a greater diversity of wheat varieties, which positively affected crop yields (Di Falco et al., 2008). Other examples in this line are the development of agroecology-based local agri-food systems in Spain (Guzmán et al., 2013; Vicente-Almazán Castro et al., 2019). A decentralized governance relying on networks of local farmers and consumers has been identified as a source of resilience to climate change in other areas of the world (Altieri et al., 2015).

One of the key links between food consumption and agricultural sustainability is the dietary choices related to the share of animal products and waste rates. In the Mediterranean region, a shift away from the Mediterranean diet has been observed in recent decades (Karamanos et al., 2002; Lassaletta et al., 2014b). This diet was ecologically adapted to the resources of the Mediterranean basin, relying on a high share of vegetables and fruits, olive oil, whole cereals, legumes and fish, and with a low share of animal products. It has been argued that recovering the Mediterranean diet would be an effective CC mitigation strategy (Sanz-Cobena et al., 2017). The latter study also underlined the reliance on feed imports and the need for reducing food waste in Mediterranean countries, particularly in the North of the basin. Therefore, the relocalization of agriculture in the region does not seem possible without major changes in the consumption patterns of European Mediterranean countries. Moreover, Ponti et al. (2016) identified clear links between the preservation of the Mediterranean diet and the conservation of traditional Mediterranean farming systems through holistic strategies. These strategies go beyond the application of a set of practices, requiring the reinstatement of social organization and collective strategies in farmer communities that make full use of holistic knowledge about food systems. Furthermore, the rapid implementation of CC adaptation strategies requires social and economic support through appropriate policies, making it necessary to implement education and awareness initiatives (García de Jalón et al., 2013) and to reconfigure tax and subsidy schemes to make these strategies economically feasible.

4. Adaptation in crop production

Many traditional and modern agroecological practices in crop production are useful to adapt to the impacts of global change and resource depletion, even if they are not specifically developed for those functions. Fig. 5 shows a selection of agroecological practices, whose main effects on processes related to adaptation, resource conservation (e.g. energy, and water use), other regulating services, as well as provisioning, supporting and socio-cultural ecological services, are systematized based on the available literature. We can observe that these practices not only help adapting to climate change and resource depletion, but usually also have positive effects on most of the other important aspects of agricultural sustainability. Fig. 5 also shows, however, some potential tradeoffs that may arise from the application of these practices, such as lower yields or lower economic performance, which stresses the need for site-specific, participatory studies in which the specific problems in each situation are identified, and the practices are correspondingly tailored to overcome the problems. These practices are further discussed in the following subsections, in which they are classified into those related to biodiversity management (Section 4.1), soil organic matter management (Section 4.2) and reduced use of fossil fuels (Section 4.3).

4.1. Biodiversity management

Diversification strategies include both cultivated/domesticated and wild species, and can take place at different scales, from farm to regional or global scales. The performance of some key biodiversity-related practices, including agroforestry, crop rotations, cover crops, absence of pesticides and local varieties, are analysed in Fig. 5. Diversification has been identified as one of the best strategies to increase

	Adaptation	Regulation									Provision	Support	Socio-Cultural		
	Resiience / adaptability	Microclimate	GHG mitigation	Soil Organic Matter	Erosion control	Energy use	Water use	Reduced nutrient surplus	Reduced chemical pollution	Pest, disease and weed regulation	Productivity	Biodiversity	Employment	Economic performance	Socio-Cultural, other
Agroforestry	1-3	4; 5	6	7	6; 8		5; 6	6; 9-11	11	1; 12	3; 4; 6; 13-15	8	4; 16	4; 6; 16; 17	2; 4
Crop rotations	18; 19			20; 21	1	22	1	23		24; 25	18; 20; 21; 23; 26; 27	24; 25		26	
Cover crops	1	28	29; 30	31-35	34; 36-42*	28; 29; 38; 43	28; 35; 36; 39-42; 44; 45*	35; 40; 45-47	40	28; 35; 41; 46; 48-50	28; 30; 34-36; 38; 41-46; 49-51	35; 46; 52-54*	28; 43; 55	41; 49; 54; 56; 57	
No pesticides / certified “organic”	58		59-64	32	1	59; 64-68	64; 69; 70	71	72	73; 74	34; 59; 64-69; 71; 73-75*	34; 76-80*	68; 75	61; 68; 75	
Local varieties/species	81-88		89; 90	89			88; 91			74; 87; 92-94	27; 74; 82; 84; 86; 87; 89; 91; 95; 96	92		84	87; 97-99
Organic inputs	100; 101		60; 90; 102	31-33	39*	102; 103	39; 100*	46; 102-104	101; 102; 104-112	46; 50; 113-117	27; 34; 46; 47; 50; 100; 103; 104; 118*	46; 114; 119-121			
Reduced tillage	1		34; 90; 122; 123	31-34	36; 39; 42*	22; 122; 124	36; 39; 42*	104; 123	104	25; 125-127	20; 22; 27; 34; 42; 104; 123-127	25; 77; 126-128	22; 43	118; 129	
Terracing	2; 100; 130	131		132; 133	39; 132; 134; 135 *		39; 100; 130*	132			100	2	55	130	2; 130; 131
Renewable energy						136; 137			138					137-141	

Fig. 5. Selected agroecological practices for climate change adaptation in crop production, and their socio-environmental performance under Mediterranean conditions. Green represents generally positive responses (> 75% positive), red generally negative responses (> 75% negative), yellow mixed or neutral responses, and grey lack of data. Dark colours represent evidence from Mediterranean climate areas obtained by meta-analysis, medium colours represent evidence from Mediterranean areas obtained in non-systematized field studies, and light colours represent evidence not specific of the Mediterranean climate.
*These cases represent situations in which a meta-analysis is available but its coverage is incomplete or the results are inconclusive. In those cases, primary studies have been used to complement the meta-analysis results. These cells have been coloured dark if the primary studies confirm the trends reported in the meta-analysis, and medium if the results are different. See details in Supplementary Information.
[1] Rosa-Schleich et al. (2019); [2] Brunori et al. (2018); [3] Arenas-Corraliza et al. (2018); [4] Pantera et al. (2018); [5] Lin et al. (2018); [6] Kay et al. (2019); [7] Chatterjee et al. (2018); [8] Torralba et al. (2016); [9] Palma et al. (2007); [10] Gikas et al. (2016); [11] Pavlidis et al. (2018); [12] Pumarino et al. (2015); [13] Mahieu et al. (2016); [14] Moreno et al. (2007); [15] Campi et al. (2009); [16] Campos et al. (2008); [17] Blanc et al. (2019); [18] Borrelli et al. (2014); [19] Bonciarelli et al. (2016); [20] López-Fando and Almendros (1995); [21] Ryan et al. (2008); [22] Taner et al. (2016); [23] Melero et al. (2011); [24] Cirujeda et al. (2019); [25] Santin-Montanya et al. (2018); [26] Yigezu et al. (2019); [27] Benlhabib et al. (2014); [28] Canali et al. (2013); [29] Guardia et al. (2019); [30] Diacono et al. (2019); [31] Vicente-Vicente et al. (2016); [32] Aguilera et al. (2013); [33] Francaviglia et al. (2019); [34] Lee et al. (2019); [35] Shackelford et al. (2019); [36] Ruiz-Colmenero et al. (2011); [37] Ruiz-Colmenero et al. (2013); [38] Robačer et al. (2016); [39] Maetens et al. (2012); [40] Zuazo et al. (2011); [41] Eshel et al. (2015); [42] Almagro et al. (2016); [43] Diacono et al. (2017); [44] Delpuech and Metay (2018); [45] Smukler et al. (2012); [46] De Leijster et al. (2019); [47] Farneselli et al. (2018); [48] Salmeron et al. (2019); [49] Urbano et al. (2006); [50] D'Amore et al. (1999); [51] Garcia et al. (2018); [52] Carpio et al. (2017); [53] Castro-Caro et al. (2015); [54] Correia et al. (2015); [55] de Graaff et al. (2010); [56] Mohamad et al. (2018); [57] Hijbeek et al. (2019); [58] Lesur-Dumoulin et al. (2017); [59] Michos et al. (2012); [60] Mohamad et al. (2016); [61] Mohamad et al. (2014); [62] Aguilera et al. (2015a); [63] Aguilera et al. (2015b) [64] Litskas et al. (2019); [65] Alonso and Guzmán (2010); [66] Litskas et al. (2011); [67] Ronga et al. (2019); [68] Sartori et al. (2005); [69] Duran-Zuazo et al. (2019); [70] Wheeler et al. (2015); [71] Campanelli and Canali (2012); [72] Laini et al. (2012); [73] Martinez-Eixarch et al. (2017); [74] Annicchiarico and Pecetti (2010); [75] de Graaff et al. (2011); [76] Armengot et al. (2011); [77] Armengot et al. (2012); [78] Aleixandre-Benavent et al. (2017); [79] Puig-Montserrat et al. (2017); [80] Ponce et al. (2011); [81] Annicchiarico et al. (2011a); [82] Al-Abdallat et al. (2017); [83] Allel et al. (2019); [84] Annicchiarico et al. (2005); [85] Annicchiarico et al. (2013); [86] Annicchiarico et al. (2017); [87] Brush and Meng (1998); [88] Chamekh et al. (2016); [89] Carranza-Gallego et al. (2018); [90] Litskas et al. (2017); [91] Gouesnard et al. (2016); [92] Carranza-Gallego et al. (2019); [93] Alp and Sagir (2009); [94] Czembor and Czembor (2000); [95] Sanna et al. (2014); [96] Lakew et al. (2011); [97] Abu-Alrub et al. (2004); [98] Biasi et al. (2015); [99] Brugarolas et al. (2009); [100] Kuzucu (2017); [101] Lakhdar et al. (2008); [102] Bartzas and Komnitsas (2017); [103] Lopez-Fando and Pardo (2013); [104] Debiase et al. (2018); [105] Montemurro et al. (2010); [106] Lakhdar et al. (2009); [107] Montemurro et al. (2008); [108] Montemurro and Maiorana (2007); [109] Montemurro et al. (2007); [110] Montemurro et al. (2005a); [Montemurro et al. (2005b); [112] Montemurro et al. (2004); [113] Amenduni et al. (2008); [114] Bonilla et al. (2015); [115] Gilardi et al. (2013); [116] Gilardi et al. (2014); [117] Gilardi et al. (2015); [118] Pala et al. (2008); [119] Garcia-Alvarez et al. (2004); [120] Bonilla et al. (2012); [121] Sanden et al. (2019); [122] Lovarelli and Bacenetti (2017); [123] Dachraoui and Sombrero (2020); [124] Hernanz et al. (2014); [125] Mazzoncini et al. (2008); [126] Sans et al. (2011); [127] Armengot et al. (2013); [128] Boscutti et al. (2015); [129] Kassam et al. (2012); [130] Zoumides et al. (2017); [131] Tucci et al. (2019); [132] Hammad et al. (2006); [133] Moraetis et al. (2015); [134] Tarolli et al. (2014); [135] Sanchez-Maranon et al. (2002); [136] Aguilera et al. (2019b); [137] Marucci and Cappuccini (2016); [138] Bardi et al. (2013); [139] Carroquino et al. (2015); [140] Baquero et al. (2011); [141] Viccaro et al. (2019)

adaptiveness of farming systems (Darnhofer et al., 2010a). A recent global study (Renard and Tilman, 2019) has found that country-level crop diversity has a yield stabilizing effect "that is similar in magnitude to destabilizing effects of variability in precipitation. This greater stability reflects markedly lower frequencies of years with sharp harvest losses". Biodiversity provides a buffer capacity against environmental risks, helping to maintain the functioning and productivity of ecosystems under CC (Jackson et al., 2010). Higher biodiversity levels in organic farming systems (Bengtsson et al., 2005) have been associated to pest control potential (Muneret et al., 2018), and economic and ecological stability (Muller, 2009). Higher biodiversity is a very desirable trait in a context of an expected reduction in biodiversity as a result of CC in the Mediterranean basin (Lloret et al., 2004). Within Europe, a particularly high diversity in farm size and management intensity has been identified in Mediterranean regions, which was found to reduce the vulnerability of regional wheat yields to climate variability (Reidsma and Ewert, 2008). Legumes constitute an essential component of the biodiversity of Mediterranean cropping systems and of the Mediterranean diet. For example, fava beans are a popular food in the Mediterranean area, where this crop is adapted to low-water conditions (Multari et al., 2015). Nonetheless, legume cultivation has sharply declined in recent decades in Mediterranean countries such as Spain (Lassaletta et al., 2014b). The re-introduction of minority crops (i.e. crops cultivated in small quantities, usually for self-consumption or local markets), however, faces multiple challenges, such as a lack of availability of improved varieties, plant protection methods, crop-specific agronomic knowledge, or logistical constraints (Meynard et al., 2018).

The presence of trees in arable systems (agroforestry) has multiple benefits for adapting to CC. In California, the structural complexity of gardens has been shown to reduce mean and maximum temperature, and also to influence watering behaviour of gardeners, reducing the amount of water used (Lin et al., 2018). Regarding the effects on soil, a recent meta-analysis has shown an 8.5% increase in SOC stocks in silvoarable agroforestry systems under Mediterranean climate (Chatterjee et al., 2018), and a study on wheat intercropping with walnut has shown that walnut roots grow deeper with the presence of wheat (Cardinael et al., 2015). Overall, these benefits to agroecosystem functioning result in a positive impact on yields. Arenas-Corraliza et al. (2018) observed that silvoarable systems combining walnut and barley or wheat were more productive than monocultures in a Mediterranean area, particularly in years with early heat events. Likewise, Mahieu et al. (2016) found higher grain production and N concentration for chickpeas cultivated in alleys between trees than as sole crop. One of the most representative agroforestry systems of the Mediterranean are the 'dehesas' and 'montados' of South-West Europe (Section 5.3).

The use of vegetation cover has been identified as one of the most effective strategies to adapt to CC, mainly through reducing vulnerability to erosion, increasing management options during drought periods, and retention of N mineralized due to warming (Kaye and Quemada, 2017). In Mediterranean herbaceous crops, cover cropping can be applied either as substitution of bare fallow in winter crops rotations, as winter cover in summer crops rotations (Guardia et al., 2016), or as living mulch in row crops (Canali et al., 2017). Cover cropping is particularly interesting in Mediterranean woody crops, where it produces multiple physicochemical, ecological and economic benefits (Pantera et al., 2018). Thus, the presence of vegetal cover improves the chemical and biological properties of the soil, including the build-up of SOC (Vicente-Vicente et al., 2016) and the protection from erosion (Ruiz-Colmenero et al., 2013), which is highly relevant for CC adaptation given the expected increase in extreme climate events (Section 2.1). Several authors have noted an increase in wild animal species associated to the presence of cover crops, including species of conservation interest (Carpio et al., 2017; Castro-Caro et al., 2015; Giralt et al., 2018). The management of cover crops in woody systems aims to find a balance between the provision of ecosystem services and a low competition for soil resources with the main crop (Garcia et al., 2018). Given the increasing water limitation of crop growth under CC (Section 2.2), an adaptive management of cover crops is paramount in Mediterranean woody cropping systems, which underlines the need for specific research in each agro-climatic condition to find the most appropriate species and cover crop management practices (Delpuech and Metay, 2018; Robačer et al., 2016).

Landraces, i.e. local or old crop varieties may prove to be useful to cope with CC, as they are usually well adapted to their local, usually extreme environments and low-input growing conditions (Gouesnard et al., 2016; Lopes et al., 2015). For example, old wheat varieties have been shown to have a set of traits that could be beneficial for CC adaptation, particularly under organic management in semi-arid Mediterranean conditions (Carranza-Gallego et al., 2018). Some of these traits are a higher root to shoot ratio, higher biomass production, better ability to compete with weeds and higher N content in grain. A higher root:shoot ratio, harvest index variations, and allelopathy have been identified as some of the most interesting traits to investigate for crop breeding in a context of CC (Korres et al., 2016). Another adaptation strategy based on local varieties is the use of heterogenous genetic material, in the form of populations and mixtures as the basis for breeding programs (Ceccarelli et al., 2010). Moreover, the selection of native perennial ryegrasses (*Lolium perenne* L.) in Sardinia showed some very persistent and vigorous accessions (Sanna et al., 2014), while crosses of wild barley (*Hordeum vulgare ssp spontaneum*) with cultivated barley have been used to improve crop performance in low-yield environments of Syria and Jordan (Lakew et al., 2011). At the same time, making use of the wide genetic diversity of landraces across Mediterranean areas could significantly contribute to CC adaptation in each specific region, by targeting desirable traits that are not present in local landraces (Annicchiarico et al., 2011a; Mansour et al., 2018). Therefore, from an agroecological approach, the extensive diversity of old crop varieties and native genetic material of Mediterranean areas could be useful resources to obtain adaptation traits to each specific environment. Lastly, another source of productive diversity of Mediterranean agroecosystems is the use of wild edible plants, which is still widespread in the Southern Mediterranean, for example in Palestine (Ali-Shtayeh et al., 2008) and which has a rich associated traditional knowledge that could be very valuable for its application to other Mediterranean areas, but is rapidly disappearing. Although genetic and molecular knowledge can be very useful for developing new varieties adapted to CC, we argue that more research efforts should be made on in situ breeding, via collaboration between farmers and researchers, in order to promote a co-evolution of crops with the environment. In many cases, just the appropriate selection of local old varieties would suffice to improve crop performance. For example, Anderson et al. (2016) showed that farmer-participatory varietal selection can substantially contribute to closing the yield gap in rainfed crops.

4.2. Soil organic matter management

Soil organic matter, whose main component is SOC, contributes to climate adaptation through multiple ways, including (i) improving crop performance under drought conditions by enhancing the water retention capacity of the soil; (ii) decreasing erosion soil losses and water runoff by increasing the infiltration and aggregation of surface soil (Diacono and Montemurro, 2010); and (iii) increasing biodiversity and aiding in the suppression of pests (Ghorbani et al., 2008). The greater climate resilience that this confers makes the management of soil organic matter an important adaptation strategy (Lal, 2010). As discussed in Section 2.2, preventing or reversing land degradation is a priority for agricultural CC adaptation in vulnerable areas such as the Mediterranean basin. Organic matter recycling is the basis of soil fertility and crop production in agroecological systems. In a meta-analysis of studies under Mediterranean conditions, Aguilera et al. (2013) found significantly higher SOC stocks under organic farming, particularly under

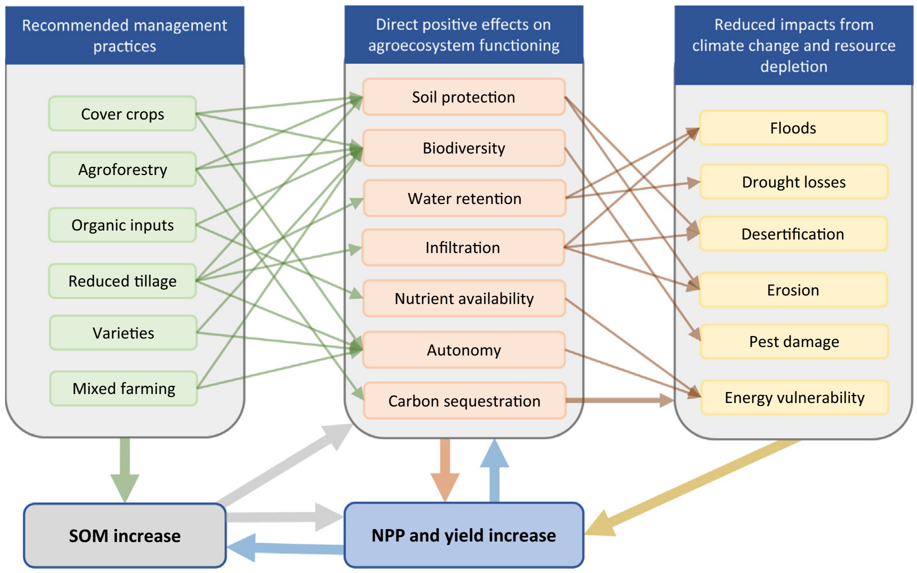

Fig. 6. Adaptation to climate change through the management of soil organic matter (SOM). Practices related to SOM management have direct effects on the agroecosystems and indirect effects through SOM increase. These effects reduce the impacts of climate change, potentially leading to a virtuous cycle through improved yields.

intensive cropping conditions and when various recommended practices were simultaneously applied. Another more recent meta-analysis has confirmed that the carbon storage potential with recommended management practices of Mediterranean soils is much higher than the 4 per 1000 initiative goals (Francaviglia et al., 2019). Probably in relation to this increase in SOC, Wheeler et al. (2015) found that Mediterranean irrigated systems under organic management consumed less water than conventional systems.

As shown in Fig. 6, an appropriate management of SOM improves soil quality and plant production in a synergistic way, and the gains in biomass productivity can be used to incorporate even higher amounts of biomass into the soil, thus further increasing SOM and plant productivity in a virtuous cycle. In addition, Fig. 6 also shows that soil management practices aimed to increase SOM do not only improve soil properties and reduce the negative impacts of CC through their direct effect on SOM, but they may also have direct beneficial effects for adaptation (Howden et al., 2007). The practices associated with the increase of SOM also tend to have a direct impact on improving crop yields in a context of CC. For example, the results of the modelling study by Liu et al. (2017), which includes some sites under Mediterranean climate, suggest that soil incorporation of residues can effectively reverse the negative impact of climate change on cereal yields, mainly due to the reduction of soil evaporation and runoff, which results in an increase in water use efficiency, particularly in hot and dry environments.

4.3. Reduced dependence on fossil fuels

Conventional agricultural production systems, particularly when intensively managed, are strongly dependent on the use of fossil fuels (Wallgren and Hojer, 2009). The absence of synthetic fertilizers and pesticides under organic farming reduces the dependence on external energy inputs and increases the efficiency in the use of fossil energy (Smith et al., 2015). This trend has also been observed in multiple studies in Mediterranean cropping systems (Fig. 7), for example in a broad set of crops in Spain (Alonso and Guzmán, 2010; Moreno et al., 2011), Turkey (Gündogmus and Bayramoglu, 2006) or Italy (Longo et al., 2017). In addition, the higher levels of SOM under organic farming reduce the need for mechanical energy for traction (Peltre et al., 2015).

However, there are some inputs, such as fuel, electricity, or the infrastructure of greenhouses that still have a mostly fossil origin under organic farming, and which lead to low non-renewable intensity

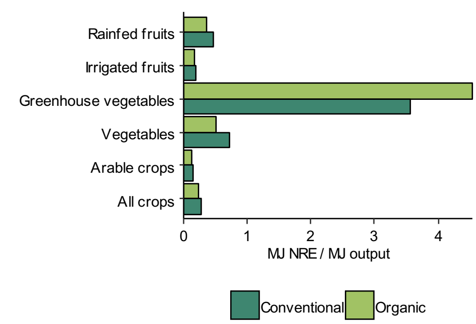

Fig. 7. Non-renewable energy (NRE) intensity of organic and conventional crop production in Spain. Elaborated with data from Alonso and Guzmán (2010)

differences with conventional systems in many situations, or even cases in which the non-renewable energy intensity is higher in organic systems (see Fig. 7). Consequently, it would be necessary to develop renewable systems to perform these functions, while also aiming to reduce other burdens of these renewable systems, such as their land cost (Guzmán et al., 2011). Bardi et al. (2013) reviewed alternatives for the use of electricity from renewable sources to power modern agriculture. They found that the major problems for the use of electricity for producing agricultural inputs were with mineral fertilizers other than N, and with pesticides. These problems are reduced in agroecological systems due to a higher reliance on organic matter recycling and the absence of synthetic pesticides. However, there is still a need to further improve and develop farm-level practices which contribute to nutrient recycling and soil organic matter accrual without relying on external inputs, such as cover cropping or mixed farming, as well as agro-food system-level practices which safely return the nutrients consumed by humans or lost as food waste back to the soil (Padró i Caminal, 2018).

Energy use in Mediterranean organic rainfed systems is usually dominated by mechanical traction (machinery and fuel) (Alonso and Guzmán, 2010; Moreno et al., 2011). In these systems, reduced tillage would significantly contribute to saving fuel, lubricants and machinery use, as well as reducing their associated environmental impacts (Lovarelli and Bacenetti, 2017), and promoting soil C sequestration (Aguilera et al., 2013). The reduction of tillage usually depends on the chemical control of weeds, but solely mechanical reduced tillage methods with good performance under organic farming are also available, such as shallow non-inversion tillage (Cooper et al., 2016). Under Mediterranean conditions, Armengot et al. (2013) found that both herbicides in conventional fields and weed harrowing in organic fields prevented yield losses caused by weeds, but, while the former reduced weed diversity by 47%, the latter maintained the same weed biodiversity values as non-weeded fields. Another agroecological practice contributing to reducing the energy needs of organic farming is cover cropping, or "agroecological service crops", as has been observed in horticultural rotations in Italy (Diacono et al., 2017). Fuel savings would also help improving the feasibility of self-producing the fuel on the farm (Aguilera et al., 2019b). Reducing fossil energy use in irrigation is also essential for the sustainability of Mediterranean agriculture. Renewable energy for irrigation can be obtained from solar or wind. Due to the intermittency of these energy sources and the seasonal nature of demand, however, there is a need for oversizing, energy storage, or hybrid systems in order to achieve economic viability (Carroquino et al., 2015). Moreover, it is paramount to limit the use of the most energy-intensive water resources, as well as to avoid extraction rates above the recharge rate of the aquifers.

5. Adaptation in livestock production

In this review, we focus on adaptation strategies in grazing systems and mixed crop-livestock systems, both of which could be considered extensive systems applying many agroecological principles. Extensive livestock production helps increase the diversity of domestic breeds able to use feed resources (pastures) that cannot be used for other forms of production, and helps to maintain high biodiversity levels (Bernués et al., 2011; Rodríguez-Estévez et al., 2012), while reducing fire risk. Adaptation strategies studied here are classified into those focused on farm management, both of livestock and pastures, and those related to diversification, including the use of indigenous breeds and species that are better adapted to the climatic conditions of each area. Fig. 8 shows the main practices reviewed, including their effects on processes related to adaptation, socio-economic performance and global change.

5.1. Management of extensive herds

A low dependence on external products and services and a greater diversification, introducing more livestock species (mainly small ruminants) and breeds, and cultivating some fodder crops, have been found to make organic extensive cattle production systems less vulnerable to the impacts caused by CC, particularly the lack of fodder during periods of drought (Escribano et al., 2014). A longer grazing season (see Section 5.3) would reduce winter supplementary feed and housing costs (Iglesias et al., 2012); however, additional housing costs may be necessary to mitigate the summer heat, and shorter springs will produce less grass and fodder, increasing feed costs. Apart from that, extensive and outdoors systems require measures such as availability and supply of fresh water and shade in grazing areas. Mancera et al. (2018) show the relationship between landscape structure and animal welfare indicators, indicating that cattle well-being can be improved in production systems associated to trees. Furthermore, artificial lakes have been identified as a useful adaptation strategy in Mediterranean drylands, although, in order to maximize the ecosystem services they provide, they have to be combined with other measures such as relocation of agricultural areas outside lake basins, afforestation of surrounding areas, and adoption of best local agricultural management practices (Santos et al., 2018). The increase in livestock and wild animals water requirements will be simultaneous, decreasing water availability and quality where these share grasslands; in this regard, Barasona et al. (2014) showed how permanent water sources act as important points of tuberculosis transmission interactions between cattle and wild boar in a Mediterranean ecosystem, making it necessary to preserve the sources of water with fences or dugouts.

Transhumance is a traditional livestock mobility practice aimed to use grazing resources efficiently on large spatial scales, benefitting from the difference in phenology among areas with contrasting climate patterns. This mobility reduces the pressure on low carrying capacity grasslands through the movement from the low areas to the high mountain pastures for the dry season. This system of seasonal movement has been traditionally widespread in the Mediterranean basin, where it has helped shape complex landscape mosaics, improved soil quality, reduced fire risks and preserved cultural values and local ecological knowledge, spanning from the Iberian Peninsula in the West (Camarero et al., 2018; Oteros-Rozas et al., 2014a) to the Taurus Mountains in the East (Ocak, 2016). The recovery of transhumance, now lost in many areas due to rural abandonment and other socio-economic factors, could be an effective strategy to adapt to CC by increasing extensive livestock production efficiency, economic viability and self-sufficiency. For example, livestock mobility has been shown to contribute to decreasing non-renewable energy dependence on extensive livestock production in Mediterranean areas of Southern France by increasing the contribution of grassland resources to feed intake (Vigan et al., 2017).

5.2. Diversification, local breeds and change of species

Livestock industrialization has meant the loss of biodiversity in this sector, with 20% of the livestock breeds currently at risk, and with an extinction rate of almost one breed per month (Rischkowsky and Pilling, 2007). This loss of biodiversity is closely related to the aim of maximizing production at the expense of abandoning traditional production systems and their associated low-productivity breeds, thus losing the ability to respond to environmental impacts (Thornton et al., 2009). Martin and Magne (2015) simulated livestock systems with different degrees of diversity in the face of CC scenarios in France, concluding that systems with greater diversity showed better adaptation capacity and less vulnerability to weather variability, achieving self-sufficiency for forage requirements without increasing feed costs. Their results confirm the possibility of increasing the adaptation capacity and reducing the vulnerability of livestock systems to CC through an increase in their diversity. Indeed, multi-species composition of herds has been identified as a strategy already applied by traditional pastoralists to survive climate extremes periods (Nyong et al., 2007) and to use different fodder resources. Another strategy applied by traditional pastoralists is the change from cattle to small ruminants. A shift from cattle to sheep and goat as an adaptation strategy to changes in climate has been recorded in the Mediterranean region as far as 8200 years ago (Roffet-Salque et al., 2018).

A major agroecological principle is to use species, genotypes and systems adapted to the environment, rather than adapting breeding conditions to the requirements of the animals (Archimede et al., 2014). Therefore, under CC conditions in the Mediterranean region, the breeds and species most resistant to drought should be chosen, which may result in less intensive livestock production systems (Dono et al., 2013). Mediterranean farmers are already responding to these trends, for example by the expansion of goats for dairy production, as this species is more tolerant to heat stress than sheep or cattle (Silanikove and Koluman, 2015). Indigenous breed animals are well adapted to the environment and local production practices (Manzano and Salguero, 2018), more resistant to illness, less productive but more robust and long lived (Novak and Fiorelli, 2010), and they also show higher thermo-tolerant capacities (Rashamol et al., 2018), as compared to cross-bred and improved breed animals. In the Mediterranean basin, local breeds have been studied as products of complex cultural and environmental processes mediated by both natural and artificial selection (Colino-Rabanal et al., 2018), giving rise to a myriad of livestock niches that are a very valuable source of genetic diversity and socio-ecological knowledge.

5.3. Pasture management

Mediterranean ecosystems are highly resilient to climate

	Adaptation	Regulation							Provision	Support	Socio-cultural	
	Adaptation / resilience	Soil Organic Matter	GHG mitigation	Erosion control	Energy use	Water use	Reduced nutrient loads	Fire management	Productivity	Biodiversity	Employment	Economic performance
Adjusting stocking rates	1; 2	3; 4	4	5; 6	1; 2; 7-15	16	4; 7; 9; 10; 16	8; 10; 11; 15; 17-20	1; 11; 15	2; 11; 12; 19; 21-28	29	1; 15; 27; 29
System diversification	30-33		7		14; 29; 30; 33-35	30	9; 14; 35	34	10; 14; 15; 30; 31; 33-36	7; 14; 25; 37	14; 29; 38	5; 10; 12; 14; 24; 29-31; 33-36; 38-40
Transhumance	41; 42	43		43	15; 41; 42	41-45	46	40; 42; 43; 46	46	25; 42; 43; 46; 47	46	42; 44; 46
Trees in pastures		5; 36; 48-52	50	39; 47; 49; 53	5; 28; 49; 54	5; 49; 52; 55	5; 49; 50; 55	5	5; 10; 27; 54	5; 27; 28; 39; 47; 49; 55		27; 36; 56
Ponds				45	32	32; 57			32	57-61		32; 45
Autochthonous breeds	33			40	10; 17; 29; 33	40		8; 40; 62; 63	29; 33; 40	4; 36; 40; 47; 62; 63	29; 40; 63	
Change of species						15			29	25; 37	8; 29	29
Majadeo/ Redileo		64			22				36; 65	36; 65		

Fig. 8. Selected agroecological practices for climate change adaptation in livestock production, and their socio-environmental performance under Mediterranean conditions. Green represents generally positive responses (> 75% positive), red generally negative responses (> 75% negative), yellow mixed or neutral responses, and grey lack of data or not applicable. Dark colours represent evidence from Mediterranean climate areas obtained by meta-analysis, medium colours represent evidence from Mediterranean areas obtained in non-systematized field studies, and light colours represent evidence not specific of the Mediterranean climate obtained by meta-analysis. See all sources and indicators in the Supplementary Materials.
[1] Aguilar et al. (2006); [2] Sternberg et al. (2000); [3] Conant et al. (2017); [4] Mondelaers et al. (2009); [5] Moreno and Pulido (2009); [6] Lasanta et al. (2001); [7] Mena et al. (2014); [8] Boza et al. (2007); [9] Dumont et al. (2013); [10]Díaz-Gaona et al. (2014b); [11] Ripoll-Bosch et al. (2013); [12] Nardone et al. (2004); [13] Rodríguez-Estévez et al. (2012); [14] Correal et al. (2006); [15] De Rancourt et al. (2006); [16] Van den Broeck et al. (2019); [17] Riedel et al. (2007a); [18] Casasus et al. (2007); [19] Hadjigeorgiou et al. (2005); [20] Garcia-Ruiz and Lana-Renault (2011); [21] Ravetto Enri et al. (2017); [22] González de Tanago et al. (1984); [23] Benton et al. (2003); [24] Riedel et al. (2007b); [25] Bignal and McCracken (2000); [26] Perevolotsky (2006); [27] Rodríguez-Estévez et al. (2012); [28] Sá-Sousa (2014); [29] Díaz-Gaona et al. (2019); [30] Malek and Verburg (2018); [31] Reidsma and Ewert (2008); [32] Roggero et al. (1996); [33] Olaizola et al. (2015); [34] Landau et al. (2000); [35] Cocks and Thomson (1988); [36] Montoya Oliver et al. (1988); [37] Metera et al. (2010); [38] Jouven et al. (2010); [39] Eichhorn et al. (2006); [40] Delgado-Serrano et al., 2019 ([41] Schilling et al. (2012); [42] Oteros-Rozas et al. (2013); [43] Oteros-Rozas et al. (2014b); [44] Nadal-Romero et al. (2018); [45] Schnabel et al. (2009); [46] UPA (2009); [47] San Miguel-Ayanz (2001); [48] Sanchez et al. (2010); [49] Munoz-Rojas et al. (2015); [50] Moreno et al. (2018); [51] Moreno et al. (2007); [52] Muñoz et al. (2007); [53] Joffre (1992); [54] Ruiz-Perez (1990); [55] Gaspar et al. (2007); [56] Blaser et al. (2013); [57] Escribano et al. (2014); [58] Beja and Alcazar (2003); [59] Zacharias and Zamparas (2010); [60] Zacharias et al. (2007); [61] Bagella et al. (2016); [62] Casas et al. (2011); [63] García Romero et al., 2019; [64] Díaz-Gaona et al. (2014a); [65] Labrador Moreno (1993); [66] Meson García (1989)

disturbances (Bussotti et al., 2014). Their plants have evolved to adapt to periodic droughts, and they can cope with moderate increases of droughts driven by CC (Jongen et al., 2013). The adaptive responses to periodic droughts of Mediterranean plants may also have indirect benefits for adaptation. For example, the increased allocation of biomass belowground under drought conditions could help protect the soil against erosion and degradation (Sardans and Penuelas, 2013), although these authors also identified worrisome trends resulting from the interactions between CC and local human-driven disturbances.

In a recent review, Ergon et al. (2018) concluded that breeding grassland species for CC adaptation, both in Nordic and Mediterranean areas, should not only aim to improve plant performance under more stressful conditions, but also increase plant diversity as a general adaptation strategy. In this process, the variety of pedoclimatic conditions of the Mediterranean region should also be acknowledged. For example, Annicchiarico et al. (2011b) found that completely summer dormant cultivars of cocksfoot (*Dactylis glomerata* L.) were the most adapted to severe drought, being most suited for Northern Africa, while non-dormant or incompletely dormant cultivars were more suitable in Southern Europe. Similarly, hardseededness is a key characteristic in choosing annual pasture legume species.

Grassland management may be key to counter-act the negative impacts of CC on livestock production and soil quality. The shortening of the spring grass growth will increase the costs of supplementary feed during this season. In places where it is not possible to extend the grazing season or move the animals to better areas, the conservation of excess pasture production, such as silage or hay, may be effective adaptation measures to apply (Howden et al., 2007; Iglesias et al., 2012). Experiments in other climate regions have shown that management-intensive grazing can boost SOC levels in grasslands (Machmuller et al., 2015). In spite of this, the effect of grazing on grassland SOC is highly dependent on the climate type (Abdalla et al., 2018), so specific experiments in Mediterranean areas are required. There is an interesting traditional management practice in Spain called "majadeo" (meaning dunging), consisting of enclosing the sheep herd at a high density in a portable pen that it is moved every night to specific areas, not only fertilizing the soil but also increasing SOM and boosting the growth of some useful grassland species, some of them with endozoochory seed dispersal (Rodríguez-Estévez, 2006).

Agroforestry is probably the most promising strategy to increase resilience and maximize ecosystem services in Mediterranean grasslands. The presence of trees in pastureland helps buffer thermal extremes, conserving soil moisture or reducing wind speed (Sanchez et al., 2010). Francaviglia et al. (2012) found that silvo-pastoral systems could store more SOC under a CC scenario, compared with other land uses. Moreover, sparse tree landscapes could improve groundwater recharge as compared to treeless or forested landscapes (Ellison et al., 2017). An interesting and well-studied example of Mediterranean agroforestry system is the Dehesa (Spanish) or Montado (Portuguese) of the Iberian Peninsula, with similar examples in other areas of the Mediterranean basin, such as Morocco (Bugalho et al., 2011), Italy (Cappai et al., 2017) or Greece (Plieninger et al., 2011). They are savanna-like ecosystems with a tree layer dominated by *Quercus* spp. and an herbaceous pasture layer, which may be rotated with annual crops. The scattered trees provide forage in the form of acorns, direct tree fodder and prunings, as well as firewood and highly-valued cork. They also have important ecological functions that contribute to the adaptability of these agroecosystems, including the regulation of microclimate, water dynamics, nutrient cycling and soil fertility, among others (Moreno and Pulido, 2009). Deep roots of oaks in 'dehesas' allow them to acquire water and nutrients from deep soil layers, thus increasing the overall biomass productivity of the agroecosystems (Jongen et al., 2013). They also increase soil fertility (Moreno, 2008), SOC storage (Cappai et al., 2017) and biodiversity (Ramirez-Hernandez et al., 2014). Scattered trees have also been identified as an effective strategy to facilitate adaptative responses in agroecosystems, such as multi-directional movements of biota (Manning and Philip, 2009). The agroecological approach shows that the search for solutions to sustainability challenges can greatly benefit from traditional and scientific ecological knowledge of the interactions between organisms with the environment, usually leading to more effective solutions than with approaches based on technological inputs. For example, the recruitment of oak seedlings has been found to be improved by the plantation of acorns beneath the canopy of shrubs but not with supplementary drip irrigation (Jose Leiva et al., 2015). The regeneration of dehesas through shrub cutting may reduce biodiversity unless combined with grazing (Tarrega et al., 2009), reflecting the dominant role of grazing in preserving the biodiversity of these agroecosystems. In spite of this, the presence of patches with high tree and shrub density and diversity has been shown to increase the number of insectivorous birds and reduce cork oak tree defoliation in Iberian 'montados' (Pereira et al., 2014), underlining the role of mosaic landscapes in both biodiversity conservation and the productivity of these agroecosystems.

Fires are one of the major threats facing the Mediterranean basin in a context of CC. The increase in the risk of destructive mega-fires indicates the failure of conventional fire suppression strategies (Section 2.1). Prescribed fires are gaining attention as more effective fire management tools in Mediterranean areas (Pique and Domenech, 2018), but they have to be carefully applied to avoid risks for biodiversity (Enright et al., 2014). The combination of low-frequency fires and moderate grazing has shown to promote endemic species conservation in the SW Mediterranean basin (Paniw et al., 2017). In this context, traditional land management practices appear as potentially effective tools for preventing mega-fires and other negative impacts of forest abandonment. Fire regimes and animal husbandry have been closely interlinked in Mediterranean agroecosystems over millennia. Fires were used to improve pasture production and feed quality (Ruiz-Mirazo et al., 2012), while grazing and the clearance of forest patches helped to prevent the expansion of wildfires. For example, the dissolution of the "Mesta", a large transhumance livestock organization, by the late 19th century, has been related to the increase in forest wildfires in Central Spain (Camarero et al., 2018). At present, the livestock stocking rate in Northern Mediterranean forests, shrublands and grasslands is well below carrying capacity due to land abandonment (Papanastasis, 2009; Soto et al., 2016), diminishing the effectiveness of livestock for fire prevention (Evlagon et al., 2012). Fernandes (2013) identified fuel management as the key strategy to manage fires in a context of CC in the Mediterranean basin, which is in line with calls for a "coexistence" with fire (Otero and Nielsen, 2017), rather than applying aggressive fire suppression strategies. When appropriately managed, goats have been identified as a very effective fuel reduction strategy in Mediterranean forests, due to their ability to feed on all the Mediterranean shrubs constituting the fuel ladder (Lovreglio et al., 2014), and both goats and sheep are effective in reducing fuel loads in fuelbreaks (Ruiz-Mirazo et al., 2011). Thus, from an agroecological perspective, the functional recovery of traditional mosaic landscapes, through the reintroduction of extensive livestock and recovery of pasture areas, the extraction of woody biomass at sustainable rates, the expansion of native broadleaved species with low flammability (Dehane et al., 2017), or the expansion of 'dehesa' agroecosystems (with low tree density and pasture production), could be effective ways to reduce the risk of destructive fires while obtaining other major benefits for sustainability. These benefits may include: (i) the reduction of imported feed dependence, and consequently of the impacts of its production outside the Mediterranean basin (Sanz-Cobena et al., 2017); (ii) the production of renewable energy (biomass), thus reducing the heavy dependence on fossil fuels in Mediterranean areas (Section 2.2); (iii) the increase in biodiversity, which benefits from mosaic landscapes (Marull et al., 2015); (v) the increase in plant productivity, e.g. when shrublands are cleared for pasture regeneration to avoid fire risk (Lasanta et al., 2009) or when tree growth is enhanced due to removal of understory by grazing (Papanastasis, 2009); (v) landscape and socio-economic benefits (Lasanta et al., 2015).

6. Conclusions

The expected trends in weather patterns and availability of resources endanger agricultural production in the Mediterranean basin, making it necessary to urgently adopt measures to increase the resilience of production systems. The interconnected nature of the problems makes systemic responses imperative in order to tackle the present challenges. In this context, agroecological practices have a high adaptation potential through the cocreation of local knowledge based on the integration of scientific and traditional ecological knowledge.

Diversification, organic matter management and reduction of external inputs are three broad strategies for agroecological adaptation in cropping systems identified in the Mediterranean region. Extensive livestock production systems could adapt by herd management practices such as transhumance and herd diversification, and pasture management practices such as adjusting stocking rates and agroforestry. There is a high potential to help addressing the challenges imposed by changing fire regimes through livestock grazing, by controlling fuel loads and connectivity.

Most of the agroecological adaptation practices reviewed show synergies with the mitigation of greenhouse gas emissions and the other environmental impacts, which are required to keep food production within safe planetary boundaries. This also implies combining them with changes in the agri-food system. These changes include the recovery of the Mediterranean diet, reductions in food waste, and the relocalization of food production. Local food chains can help increase resilience by improving waste recycling, farm diversity, and farmers autonomy.

More research and public support are needed to fully develop the potential of agroecological practices for adaptation to CC through adaptive knowledge cocreation among researchers, farmers and other stakeholders. There is a clear need for developing practices tailored to local conditions, which are highly diverse in the Mediterranean basin.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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