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Agroecological strategies for innovation and sustainability of agriculture production in the climate change context: a comparative analysis between California and Italy

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Agriculture is profoundly affected by climate change, with regions like California and Italy experiencing significant challenges due to rising temperatures, altered precipitation patterns, and extreme weather events. Climate change is expected to reduce yields of specialty crops by up to 30% due to lower productivity and crop failure. To cope with climate change, farmers need to modify production and farm management practices, especially adopting agroecological principles. This mini-review explores climate change impacts on agriculture through an innovative approach that seeks to compare possible response strategies in two distant regions, California and Italy, which share similar climate conditions and crops. California's agriculture, renowned for its specialty crops like nuts, fruits, and vegetables, faces intensifying droughts, reduced snowpack, and increased potential evapotranspiration, threatening water availability and crop yields. Similarly, Italy, a Mediterranean climate change hotspot, endures higher temperatures, declining rainfall, and frequent extreme events, impacting key crops like grapes, olives, and tomatoes. Both regions see vulnerabilities compounded by climate-induced pest pressures and water scarcity. Agroecology emerges as a promising solution to mitigate these impacts by enhancing soil health, conserving water, and promoting biodiversity. Practices such as cover cropping, crop diversification, organic mulching, and precision irrigation bolster resilience. Site-specific strategies and policy support are crucial for adoption, especially in small-scale farms. Collaborative knowledge-sharing between California and Italy can foster innovative solutions, ensuring sustainable and resilient agricultural systems in the face of climate change.

KEYWORDS

resilience, soil health, drought, mediterranean climate, biodiversity, policy analysis, climate adaptation

1 Introduction

The anthropogenic causes of climate change have been scientifically demonstrated, resulting in an increasingly various pattern of meteorological and hydrological events around the planet, from heat waves to coastal flooding during extreme tides and storms, flooding from more intense precipitation events, and severe drought periods (Mann and Gleick, 2015; IPCC, 2023).

Industrial agriculture contributes significantly to climate change, especially in its release of methane and nitrous oxide from livestock and land use change (Clark et al., 2020). Agriculture, like all biological processes and human activities, is under siege from the impacts of climate change and in an unknown scenario (Ripple et al., 2023). Climate change may affect crops' productivity with changing precipitation and temperature patterns, but also leading to higher frequency in extreme events and exacerbating pest and disease pressure on crops (Burdon and Zhan, 2020). Warmer temperatures may favor some crop pests; besides, they can react differently to precipitations, depending on their exact timing and amount (Skendzic et al., 2021). Climate change may also increase or decrease weed pressure and incidence, depending on many causes and different weed-crop species combinations (Shahzad et al., 2021). Ironically, some of the most important agriculture regions of the planet are threaten by water-scarcity problems, especially in future years, such as the arid southwestern USA (e.g., California's San Joaquin and Imperial-Coachella Valleys) or the Mediterranean region (e.g., Italy) (Abd-Elmabod et al., 2020; Corwin, 2020). In fact, California and Italy represent two key agricultural regions with globally significant production but are extremely vulnerable to the impacts of extreme climate events and for these reasons they have been considered as relevant geographical areas for this study. This mini-review discusses the climate change impacts on the agriculture sector of two different and very far geographical regions, California and Italy, which, however, share many climatic conditions and cultivated crop species (Figure 1). The present study seeks to highlight how the adoption of agroecological principles, adapted as site-specific farming practices, represents the real alternative to ensure climatically resilient agricultural production in future decades.

2 Climate change impacts on California agriculture

California is one of the most important and diversified agricultural regions of the world (Petersen-Rockney, 2022a). Around 50% of the nuts (such as almonds, pistachios or walnuts) and fruits (including grapes, citrus, apricots, dates, figs, kiwi fruit, nectarines, prunes, and olives) consumed in the Unites States (US) are cultivated in California (Pathak et al., 2018). Considering the high relevance and economic value of these specialty crops and their specific environmental growth requirements, agricultural production in California is highly sensitive to climate change impacts.

The cumulative co-manifestation of dry and warm years in the "Golden State" increases the risk of drought stresses, highlighting the significant role of high temperatures in modifying water availability and overall drought impacts on agriculture sector (Mann and Gleick, 2015). For these reasons, California represents a valid case study to explore how agriculture sector is impacted but can also react to climate change and climatic extreme events, especially drought conditions (Petersen-Rockney, 2022b). Extreme weather events in the State, including more frequent heatwaves, heavy and extended drought conditions, floods are negatively

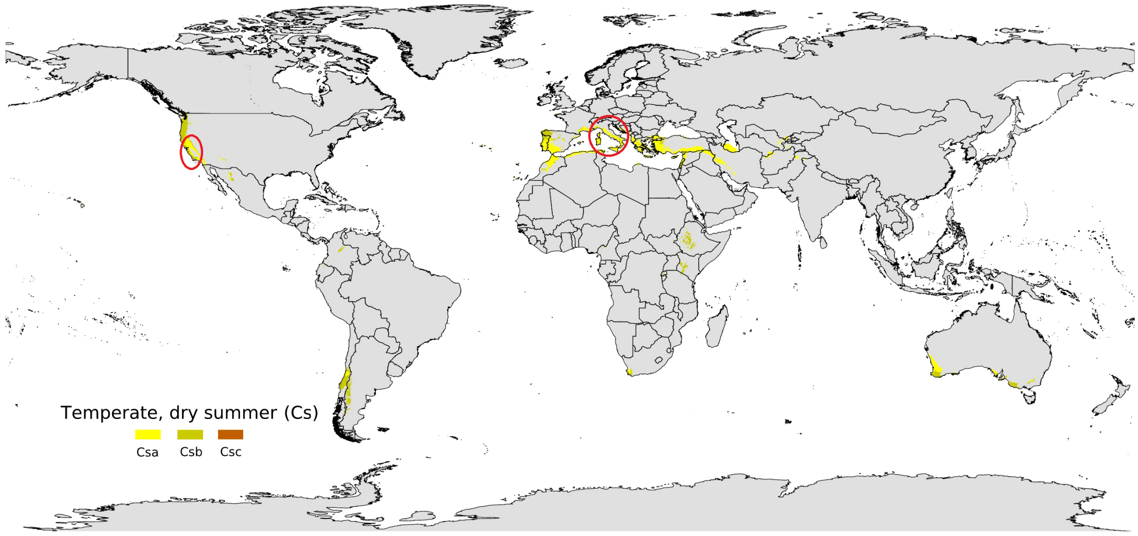


FIGURE 1
Global distribution of the Mediterranean climate (Cs) areas, following the Köppen–Geiger climate classification (Beck et al., 2018). California and Italy are marked in red among the main five global regions with this type of climate (California, Mediterranean basin, Chile, South Africa, Australia). Csa, Hot-summer Mediterranean climate; Csb, Warm-summer Mediterranean climate; Csc, Cold-summer Mediterranean climate.

impacting agriculture (Pathak et al., 2018; Weiskopf et al., 2020) and are estimated to increase in their intensity and frequency (IPCC, 2023). Analyzing California's climate data over the past four decades, autumn precipitation has decreased by 30%, while temperatures have increased by about 1°C (Goss et al., 2020). Average temperature increases projections predict that higher temperatures will be more evident during the summer season than in the winter and there will be more warming in inland areas than in coastal regions (Pathak et al., 2018).

Regarding future precipitation scenarios, California will maintain its Mediterranean climate with moderately cold and wet winters and hot dry summers (Pathak et al., 2018). Different general circulation models forecast that Northern California may experience higher annual precipitation amounts and probably more frequent storm events, while the overall state and especially Southern California are projected to be 15 to 35% drier by 2100 (DWR, C.D.o.W.R, 2015). In fact, almost 80% of the California's water in a typical year is provided by snow (Pathak et al., 2018). Provisional climate models suggest that 65% snowpack losses might occur by 2100, due to global warming (DWR, C.D.o.W.R, 2015). Generally, California's climate is shifting toward a flood–drought pattern, also resulting in increased flood risks (Pathak et al., 2018).

Even if climate change globally impacts have been in-deep studied for main field crops, major impacts in California are related to "specialty crops", defined by the United States Department of Agriculture (USDA) as all fruits (e.g. grape), nuts, vegetables (e.g. tomato), and nursery crops, which account for the highest economical production of Californian agriculture (Kerr et al., 2017). This unique relevance is possible because of California's Mediterranean climate (exclusive in North America) and the large-scale supply systems for irrigation water. Grapes and tomatoes represent more than 20% of California "specialty crops" value (Kerr et al., 2017) and their importance for the agricultural sector could be considered similar also in the Italian agriculture.

The majority of specialty crops in California is irrigated, and around half of this irrigation is provided by groundwater (Cooley et al., 2015). Even if irrigation water could disguise the impacts on yields of climate change, potential evapotranspiration in California's specialty crop growing regions will significantly increase, according to the future climate scenario (Kerr et al., 2017). Already for several years and more and more now, there are increasing concerns about whether California can continue to satisfy its massive water demand for industrial purposes, agriculture production, preserving ecosystems, and developing cities in the midst of drought (Christian-Smith et al., 2015).

Besides worsening pathogens or insect pests (Trumble and Butler, 2009; Jha et al., 2024) pressure on crops, driven by climate change, it's estimated that, with a global warming trend of 3°C, weed species pressure in California and the central Midwest will substantially increase, for example considering itchgrass or witchweed (Anwar et al., 2021). Considering that the profitable value of specialty crops production is not simply related to yields but also to several quality characteristics (for example aesthetic features, shape, size or chemical composition), the majority of Californian agriculture production is particularly susceptible to climate change impacts (Pathak et al., 2018).

3 Climate change impacts on Italian agriculture

Mediterranean countries, such as Italy, have been recognized as climate change "hot spot", since the incidence of high temperature extremes is estimated to increase by 200 to 500%, considering future greenhouse gas emissions scenarios (Nikolaou et al., 2020). The effect of climate change in Italy is increasingly perceived by citizens. In 2021, a Eurobarometer analysis highlighted that climate is the fourth concern for Italian citizens, following diseases, economy, and world hunger (De Leo et al., 2023). Similarly to California, drought is a raising challenge for Italy's agricultural sector, causing a problem for the country's major crops, as well as smaller farmers (OECD/FAO, 2021).

Average temperatures in the Mediterranean region are rising faster than the global average (Dari et al., 2023). Moreover, rainfall across the region is expected to decrease by 10% to 60% (Dari et al., 2023), exacerbating water scarcity issues, crucial for Italy's water-intensive crops like rice and corn (Straffelini and Tarolli, 2023). Droughts, like those observed in recent years, have already caused significant yield reductions, while sudden storms and hail have damaged vineyards and olive groves, two pillars of Italian agriculture (Aguilera et al., 2020; Santos et al., 2020).

The largest decreases in productivity for Italy are expected for crops with a spring-summer cycle, especially if they are not irrigated, with yield reductions especially for corn, sunflower and sugar beet, while slight increases are expected for wheat (Hristov et al., 2020). Webber et al. (2018) reported that heat stress does not increase for corn and wheat crops under non-irrigated conditions, while water stress only intensifies for corn (with yield decreases in Italy around -20% values) and not for wheat (which instead shows stable yields or even increases of up to +20% in some areas of the country). Declines in rainfall directly impact crop yields. Corn, a major crop in northern Italy, relies on consistent irrigation, which is now threatened by shrinking water supplies from rivers like the Po river (Hristov et al., 2020). The projected raise in air temperature and changes in rainfall may cause a shortening ranging from 1.5 to 3 days in tomato phenology, triggering an overall 15% reduction in tomato yield (Cammarano et al., 2020).

Among tree corps, grapes, essential for Italy's globally renowned wine sector, are highly sensitive to temperature changes. Some regions may need to adapt by shifting vineyards to higher altitudes or adopting heat-resistant varieties, in order to maintain production and quality standards (Droulia and Charalampopoulos, 2021). Olive trees, resilient to drought, are now facing challenges from rising temperatures and the proliferation of pests like the olive fruit fly, which thrives in warmer climates (Aguilera et al., 2020).

The economic levy of climate change on Italian agriculture is significant, with damages from extreme weather estimated at over €14 billion in the last decade (De Leo et al., 2023). Climate change disrupts rural livelihoods, reducing employment opportunities and exacerbating rural depopulation. Small-scale farmers, who dominate the Italian agricultural landscape, are particularly vulnerable due to limited resources for adaptation (De Leo et al., 2023).

4 Agroecology and climate change resilience in California and Italy

Agroecology, integrating ecological principles into agricultural practices, offers a promising path to strengthen climate resilience by enhancing soil health, water efficiency, and ecosystem services (Altieri et al., 2015). Agroecology provides the best agricultural approach capable of coping with future challenges, by promoting high levels of diversity and resilience, while producing acceptable yields and ecosystem services (Altieri and Nicholls, 2020). Agroecology promotes the regeneration of the landscapes in which farming systems are present, improving the ecological networks, that may help in pathogens and pests prevention (Altieri and Nicholls, 2004).

California farmers will be challenged to adopt adaptation strategies in the future. In fact, California's agriculture faces significant threats from climate change, particularly due to intensifying droughts and extreme weather events.

On the other side of the Atlantic Ocean, the vulnerability of Italian agroecosystems is a specific component of total changes affecting the Mediterranean basin, characterized by biodiversity loss, freshwater overemployment, disturbed nutrient cycles, soil losses and different fire patterns. This context is exacerbated in Italy by conditions of high population density, water scarcity, high dependence on material and energy imports, combined with the predominance of highly specialized and poorly diverse agroecosystems (Aguilera et al., 2020). Due to the need to create resilience to these connected risks, systemic adaptation measures are straightaway needed (OECD/FAO, 2021). Agroecology is based on an holistic vision, enabling the recovery and valorization of traditional knowledge and the co-creation of new local knowledge, for enhancing resilience (Aguilera et al., 2020).

4.1 Agroecological strategies across regions

4.1.1 Agroecology, healthy soil and water

Healthy soils are critical for water retention and drought resilience. Practices like cover cropping, reduced tillage, and compost application, applied in tree and vegetable crops, very important in California and Italy, can increase soil organic matter, enhancing its capacity to hold water (Teng et al., 2024; Diacono et al., 2016). Studies have shown that these methods improve the water-holding capacity of soils up to 30%, crucial for sustaining crops during prolonged dry periods, frequent in California and Italy (especially in the Southern areas of the country) and reduce soil erosion, essential action for steep terrains (van Zonneveld et al., 2020; Pagliacci et al., 2020). Water scarcity, exacerbated by declining rainfall and shrinking snowpack, is a critical challenge for Italian agriculture. Drip irrigation and other precision systems, often used in agroecological settings, deliver water directly to roots, reducing losses by up to 40%, compared to traditional irrigation (Nikolaou et al., 2020). Combined with techniques like rainwater harvesting and the use of drought-tolerant crop varieties, these approaches help maintain productivity during prolonged dry periods (Altieri and Nicholls, 2017; Santos et al., 2020). In Mediterranean conditions, such as Italy's agricultural main areas, adopting mulching alongside efficient irrigation reduced evaporation rates, enabling farmers to meet crop water needs, with 20% less water during drought periods (OECD/FAO, 2021; Romero et al., 2022).

4.1.2 Agroecology and biodiversity

Diversifying crops through polycultures or intercropping can stabilize yields, by spreading risk across different species, with adjusted drought and heat tolerances, even if the yields could be lower in short-term time scale (Petersen-Rockney, 2022b). Furthermore, agroecology promotes natural pest control, reducing reliance on chemical inputs that may exacerbate water pollution and biodiversity loss (Carlisle et al., 2022). Practices such as agroforestry and managed grazing improve groundwater recharge and reduce surface evaporation, increasing soil water content up to 20%, depending on the specific pedo-climatic conditions and the cultivated crops (Belmin et al., 2023). For example, planting deep-rooted perennials alongside annual crops can optimize water uptake across soil layers while providing shade and reducing heat stress on plants. Crop diversification tends to stabilize yields by spreading the risk of failure across multiple species with different drought and heat tolerance (Altieri et al., 2015; Smith et al., 2023). For instance, polycultures, including legumes intercropped with cereals, improve nitrogen fixation by approximately 10–15% and reduce the vulnerability of monocultures to extreme weather events (Księżak et al., 2023). These systems are particularly effective in Italy's arid southern regions, where climatic variability is high. As an additional diversification strategy, adopting agroforestry in Italian farms may contribute to create microclimates that reduce heat stress on plants and prevents soil erosion, with temperatures in the field crops areas between trees about 0.5-1.0°C lower than the monoculture (Piotto et al., 2024; Romero et al., 2022).

4.1.3 Agroecology and landscape

Moreover, agroecology strengthens resilience against extreme heat and storms by fostering adaptive landscapes. Windbreaks and shelterbelts protect crops from strong winds and reduce topsoil erosion during storms (Parker et al., 2023). Deep-rooted perennials, such as certain fruit trees, are better adapted to extreme weather fluctuations, offering consistent productivity under climate stress (Parker et al., 2022). Research underscores the importance of site-specific practices, as climatic conditions and soil types vary widely across California. For instance, increasing the resilience of high-value crops like almonds and tomatoes demands tailored approaches that combine agroecological methods with advanced irrigation systems (Pathak and Stoddard, 2018; Parker et al., 2022). Agroecological landscapes are inherently more resilient to storms and extreme rainfall. After intense rain events in central Italy, farms employing agroecological practices such as minimum tillage, organic mulching based also on crop residues, permanent plant soil cover, reported up to 60% less soil loss compared to conventional systems (Kassam et al., 2012; Napoli et al., 2017). Climate change intensified pest and disease pressures in Italy, but agroecology contributes to maintain ecological balance, by harnessing natural predators (Bindi and Olesen, 2010; Scotti et al., 2023). Hedgerows, flower strips or cover cropping promote the presence of beneficial insects, reducing reliance on pesticides. Studies conducted in Italy demonstrated a reduction in pest populations in common wheat or vegetable crops, adopting such practices (Magagnoli et al., 2018, 2024).

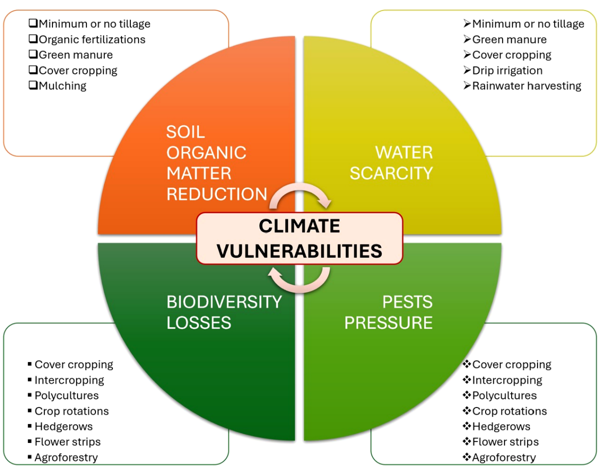
4.1.4 Agroecology, policies and socioeconomic influences

Further, funding mechanisms and extension services are pivotal in promoting agroecology. Policies that support conservation tillage, diversified cropping systems, and organic farming can encourage widespread adoption, improving agricultural sustainability across California (Carlisle et al., 2022; Belmin et al., 2023). In California's corporate agribusiness farming structure, strengthening knowledge exchange among farmers and supporting local farmers' initiatives can potentially contribute to the diffusion of agroecological practices (Kreft et al., 2023). California government support farmers to incur the high investment costs and reduce GHG emissions to adapt to water restrictions by directly funding the modernization of underground water pumps and the installation of drip or micro sprinkler irrigation systems (Zhao et al., 2023). By fostering biodiversity, improving soil health, and optimizing water use, these practices not only mitigate the impacts of drought and extreme events but also contribute to long-term overall sustainability (Teng et al., 2024). In Europe, citizens tend to pay more attention to the impacts of climate change on agricultural development (Zhao et al., 2023). As a consequence, many different strategies, initiatives, and regulations related to support agroecological approach and practices have been developed at the regional (e.g. Italy's Rural Development Program), national (e.g. Organic National Regulation), and European (e.g. Common Agricultural Policy - CAP, European Green Deal - EGD) levels (Francaviglia et al., 2023). Both the CAP and the EGD should preserve ambitious environmental commitments to avoid additional losses of the natural resources on which agroecosystems rely. These include proportional allocation of funds to each CAP goal, quantitative objectives and appropriate indicators to facilitate useful monitoring of environmental performances (Cuadros-Casanova et al., 2023). In Italy, policymakers must support agroecological practices through funding, research, and farmer education programs, considering also the fact that some agroecological practices can be labor-intensive and Italian farms tend to be small and managed by old farmers, often not well-integrated into profitable value chains (OECD/FAO, 2021). This characteristic does not facilitate a change in the agronomic management models, aimed to reduce the use of external inputs and to adopt agroecological practices that will increase the resilience of agroecosystems, highly threatened by the impacts of climate change, such as those in Italy.

4.2 Conclusion

Farmers in California and Italy are experiencing increasingly extreme climatic events (Pathak et al., 2018). At the same time, the accelerating rate and the increasing scale of climate impacts, including novel droughts and water excess conditions, reduce farmers' capacity to adopt conventional agricultural practices (Petersen-Rockney, 2022a). The adoption of alternative and site-specific practices and strategies, based on agroecological principles, will represent a successful reaction to climate impacts, both in California and Italy scenarios (Bezner Kerr et al., 2023). This study

A



B

SOCIOECONOMIC BARRIERS	
Big size farms	Small size farms
Industrial farm management	Family farm management
Long food chain	Local markets
High labor costs	High input costs
POLICY DRIVERS	
National programs (USDA)	European programs (EU CAP)
State programs	State and regional programs
Examples	**Examples**
California's Sustainable Groundwater Management Act	Italian Rural Development Programs to improve water use efficiency in agriculture
California's cap-and-trade program	CAP Eco-schemes
Water markets	Italian Rural Development Programs to increase organic agriculture models

FIGURE 2
(A) Main effects of climate change on Californian and Italian agroecosystems components and agroecological practices (in the white rectangles) that can be adopted in California and Italy, after specific and necessary adaptations to local conditions. **(B)** Comparison between Californian and Italian main possible socioeconomic barriers and policy drivers.

clearly shows the importance of international and local cooperation, especially through the exchange of knowledge and practices between regions facing similar challenges but that can react with different and local optimized practices (Figure 2). The scientific and technical cooperation, together with rational public policies, can represent a winning strategy to address the climate impacts on agriculture.

Author contributions

LN: Conceptualization, Investigation, Methodology, Writing – original draft, Writing – review & editing. SB: Supervision, Writing – review & editing. GD: Writing – review & editing, Supervision.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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