Diversification from field to landscape to adapt Mediterranean rainfed agriculture to water scarcity in climate change context

Jérôme Molénat, Karim Barkaoui, Salah Benyoussef, Insaf Mekki, Rim Zitouna, Frédéric Jacob

To cite this version:
Jérôme Molénat, Karim Barkaoui, Salah Benyoussef, Insaf Mekki, Rim Zitouna, et al.. Diversification from field to landscape to adapt Mediterranean rainfed agriculture to water scarcity in climate change context. Current Opinion in Environmental Sustainability, 2023, 65, pp.101336. 10.1016/j.cosust.2023.101336. hal-04205473

HAL Id: hal-04205473
https://hal.science/hal-04205473
Submitted on 12 Sep 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
Title Diversification from field to landscape to adapt Mediterranean rainfed agriculture to water scarcity in climate change context

Authors

Jérôme Molénat (1) *, Karim Barkaoui (2,3), Salah Benyoussef (4), Insaf Mekki (5), Rim Zitouna (5), Frédéric Jacob (1)

Affiliations

(1) LISAH, University of Montpellier, INRAE, IRD, Institut Agro Montpellier, AgroParisTech, Montpellier, France
(2) CIRAD, UMR ABSys, F-34398 Montpellier, France
ABSys, University of Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, Montpellier, France
(3) CIRAD, UMR AMAP, F-34398 Montpellier, France
AMAP, University of Montpellier, CIRAD, CNRS, INRAE, IRD, Montpellier, France
(4) INRAT, University of Carthage, Ariana, Tunisia
(5) INRGREF, University of Carthage, Ariana, Tunisia

*Corresponding author jerome.molenat@inrae.fr
Highlights

- Water scarcity threatens the sustainability of Mediterranean rainfed agriculture
- Diversification as an adaptation of agriculture to water scarcity
- Field diversification can take the form of intercropping, agroforestry and service crop
- Diversifying crops (number, abundance and spatial organization) in landscapes
- Building small-scale water harvesting infrastructures in landscapes

Keywords

agroforestry, intercropping, service crops, configuration, composition, water harvesting infrastructures, management

Abstract

Rainfed Mediterranean agriculture must adapt to water scarcity due to climate change and pressures on water resources. According to recent literature, two adaptation solutions based on the concept of diversification can be explored. The first solution is crop diversification at the field level. Three main cropping systems, namely agroforestry, intercropping and service crops, have been shown to increase soil water availability and to improve crop water use. The second solution is to consider diversification at the landscape level by diversifying crops and associated agricultural management practices (both in number, abundance and spatial organization) and building small-scale water harvesting infrastructures. In order to move towards a sustainable Mediterranean agriculture, one of the main scientific challenges ahead is to provide knowledge and tools, such as integrated agro-
hydrological models, useful to evaluate several spatiotemporal combinations of these solutions in order to optimize soil water availability and crop water use.
1. Introduction

Mediterranean agriculture (MA) has developed over the millennia by benefiting from mild to hot temperatures and adequate insolation. The population has shaped a very heterogeneous biophysical environment (soil, topography, biodiversity) by designing landscapes and agricultural practices adapted to successive periods of drought and heavy rainfall. The Mediterranean diet is recognized worldwide, based on emblematic crops such as olives, grapes, fruits, cereals and legumes (as a substitute for animal protein) ([1], Figure 1). MA is an essential economic sector and employs a large part of the population. For instance, agriculture in Maghreb contributes 10 - 20% of Gross domestic product (GDP) and employs 13 - 20% of the working population [2]. Agriculture is the primary user of water in the Mediterranean region. Crop irrigation is for instance responsible for up to 79% of the total water withdrawals in Eastern Mediterranean countries [3].

Climate change accentuates for MA the challenge of maintaining or even increasing production to feed a growing population, while simultaneously preserving natural resources such as soil, water, and biodiversity that are vulnerable to climate hazards and anthropogenic pressures. This also requires addressing potential yield gaps that may exist. Climate projections show that average temperatures will increase from 0.5° to 5.6°C, depending on the scenario, and that rainfall will continue to decrease from April to September, by about 4% per °C of global warming [4]. Sustainable management of the scarce water resource in a warmer and drier climate is one of the most crucial issues facing MA. Based on climate projections and crop modeling, water and heat waves are, and will continue to be, key limiting factors for crop production [4]. The sustainability of the Mediterranean food system will therefore depend on the sustainability of MA in a context of water scarcity.
Adapting MA to water scarcity has already been extensively studied in the field of irrigation, including new irrigation practices and technologies. Alternative water resources such as the reuse of treated wastewater and desalinated water have also been increasingly used [4]. However, new margins of progress also exist for Mediterranean rainfed agriculture in the framework of the agro-ecological transition, to optimize the use of rainfall for agricultural production. Based on recent literature, we aim to demonstrate the potential of diversification, considered at two distinct spatial levels, in facilitating the adaptation of MA to water scarcity. Firstly, at the field level, diversification can be achieved through practices such as intercropping, agroforestry, and service crops. Secondly, at the landscape level, diversification involves diversifying crops and agricultural management practices both in terms of their number, abundance and spatial organization, as well as building small-scale water harvesting infrastructures with optimal density and topology.
2. **Field diversification**

Field diversification has received increasing attention in recent years to build resilience to climate change and to improve resource-use efficiency and ecological performances of agrosystems in the Mediterranean [6]. Field diversification is a process that transforms simplified agrosystems into a more biologically and technically diverse state [7]. It consists of enhancing plant genetic, functional and/or structural diversity within cultivated fields to regulate plant competition and promote complementarity and cooperation effects resulting from ecological differences among plants, usually leading to overperformance (e.g., overyielding) compared to sole crops [8]. Plant diversity is also targeted to reduce risks regarding environmental adversity through compensation effects among plants with different environmental sensitivities. It can be achieved by multiple means (e.g., mixing varieties, species, growth forms, functional types etc.) and supported by appropriate management practices (e.g., plantation design, sowing dates, tree pruning, reduced tillage, etc.) [9]. Mediterranean regions benefit from an extremely rich heritage of diversity of crops and trees, including under-utilized or associated non-cultivated plant species, representing a unique opportunity to support field diversification [10]. In the context of water scarcity, we present here three main approaches for field diversification, namely (1) intercropping, (2) agroforestry, and (3) service crops, that would be promising for the future of MA although they would need pursuing research and engineering efforts in specifically addressing plant diversity-water relations at the field level.
Intercropping

Intercropping or polyculture is defined as the cultivation of two or more different crop species simultaneously in the same field during a growing season. In the Mediterranean, intercropping is an ancient practice consisting of mixtures of grain or fodder cereals (e.g., barley, durum wheat) and legumes (e.g., chickpea, fava bean), and to a lesser extent, of other arable crops. Intercropping has recently gained increased interest due to its potential to increase climate resilience of agriculture [11], and its well-demonstrated advantage over monocultures in terms of resource efficiency, crop yield [12], quality [13], stability [14], and provision of ecosystem services [15].

Several mechanisms are involved in regulating water balance in intercrops as compared to sole crops. When water is a limiting factor to crop production, intercropping can increase crop water uptake and water use efficiency through physiological and ecological mechanisms and optimize the overall soil moisture environment for crops [14]. Better water use efficiency is generally attributed to better water uptake in the soil profile, resulting from the exploitation of denser root systems and complementary spatial root distribution of both intercrop components species [17, 18], and to the delay between species in reaching their maximum water requirement.

For instance, in cereal-legume mixtures, the capacity of cereals to use water from deep soil layers when they reach their flowering stage allows associated legumes to use water from shallow layers while they are at their grain-filling stage, limiting water competition during sensitive stages for grain production of both species [19]. Moreover, increased dry matter accumulation rate and reduced water loss through soil evaporation and transpiration and runoff are conducive to better water utilization [20].

However, the choice of crop species and varieties, sowing densities and spatial arrangements are critical to finding the right mix achieving the expected positive outcomes from intercropping. For instance, the lack of complementarity for water can strongly limit yield advantages [21]. A
better understanding of processes underlying crop competition, complementarity, cooperation and compensation regarding water use under future dry conditions will be essential to manage and predict crop growth, water use efficiency, and yield formation in Mediterranean intercropping systems. Crop modeling has the potential to address such issues, but would require further development before being used for intercropping design purposes, mainly because they have been used for sole crops and therefore processes relevant to intercropping like plant competition and plasticity have been only rarely coded so far which could promote complementarity among associated crops [22].

Agroforestry

Agroforestry is a type of land use that combines trees and/or shrubs with crops and/or livestock in the same field for forestry, agricultural and pastoral purposes. In the Mediterranean region, agroforestry systems (AFS) have been part of the traditional forms of agriculture for millennia, and consist mainly of silvopasture and fruit tree-based silvoarable agroforestry [23, 24]. AFS are now of increasing interest because planting trees has a series of beneficial outcomes on ecological functions and services within the agricultural field and contributes to strengthening resilience to climate change [25].

Regarding the water cycle, trees act positively on multiple above- and below- ground ecohydrological processes, and they offer the opportunity to preserve water and improve the water balance at the field level. Trees can regulate the local microclimate by providing shade, thus reducing evapotranspiration [10], limiting water loss through soil evaporation, and preventing crops from severe water stress under drought [26]. By digging deep, trees can use water from deep soil reserves usually not accessible to arable crops, making the overall water harvesting more complete, and limiting water and nutrient losses through deep drainage. In addition, trees with deep roots can
activate several water redistribution mechanisms. They can lift water from deep soil layers up to the upper layers through a process known as hydraulic lift and potentially act as ‘bio-irrigators’ for the underlying crops [27]. In semiarid areas with less than 450 mm of rainfall, hydraulic lift was estimated to provide up to an additional 35-47 mm of water annually, representing around 10% of the total precipitation [28]. By creating alliances with soil microorganisms, trees can facilitate the use of water and nutrients under dry conditions [29]. As a result, AFS were shown to support higher land- and water productivities than monocultures under Mediterranean or semiarid conditions, as recently illustrated by an increase in total productivity of 10-44% in olive- [30], walnut- [31], apple- [32], apricot- [33], jujube- [34] based agroforestry. They also help mitigate the effect of increasing drought on ecosystem services in more extensive pastures [35].

However, the relevance of AFS for a drier future remains controversial in the drylands. Despite promising evidence, the positive outcomes of AFS may be counterbalanced by increased negative interactions between trees and crops with increasing aridity, which are still insufficiently understood and poorly predicted by the modeling tools available to date [36]. Indeed, most of the aforementioned facilitative mechanisms are strongly context-dependent and rely on tree species choices and management. Investigating tree species diversity, especially of native or under-utilized tree species, is needed to explore new species choices and rationalize the selection of trees with the most adapted physiological, phenological and architectural traits to agroforestry under the future drought conditions in the Mediterranean. Management practices like crown and root pruning are additional possibilities to shape tree forms, drive their functioning and optimize tree-crop interactions towards beneficial outcomes, e.g., by regulating shade or root overlap, but such practices are still in their infancy in the agroforestry context [37]. Finally, plantation design and density should also be revisited with possibly unconventional spatial patterns, i.e., not necessarily in rows as in most alley-cropping systems, and with more consideration of environmental
heterogeneity within fields to promote the overall complementarity and facilitative effects of trees in AFS.

Service crops

Service crops, also known as cover crops, are plant species grown in cultivated fields to provide supporting and regulating ecosystem services [38]. In arable agrosystems, services crops are usually sown after cash crop harvest while they are increasingly grown as intercrops in perennial agrosystems, like vineyards, olive groves, and fruit orchards. They have recognized benefits for protecting soils against erosion, nutrient leaching, and loss of organic matter, regulating weeds and pests, and preserving habitats and biodiversity. They are key components of conservation and regenerative agriculture that are developing in Mediterranean countries to face climate change [39].

Recent syntheses have highlighted positive outcomes of service crops regarding the water cycle in the fields. Compared to bare soils, service crops were shown to reduce runoff by 27% [40], deep drainage by 27-32 mm [41], and leaching by 2.5-fold, especially those caused by heavy rain events, which are increasingly frequent in the Mediterranean [42]. They also contribute to reducing soil albedo and evaporation, thus potentially increasing soil water content, mainly through mulching effects, either as live plants or residues left after destruction. In the long term, the improvement of soil organic matter content and soil aggregation promoted by service crops may lead to enhanced rain harvest through improved soil hydraulic properties (e.g., better infiltration) and soil water storage capacity. They have indirect effects on crop water productivity by limiting weed colonization and therefore water competition.

However, drawbacks specific to water-limited regions need to be accounted for when
introducing service crops under climate change. Below 700 mm of annual rainfall, service crops were shown to reduce soil water content by 18% and subsequent crop yield by 7% on average [43] because water supply cannot compensate for the transpiration of water by service crops. Similarly, the reduction in drainage can have detrimental consequences on groundwater recharge because the observed drainage reduction may be close to the annual recharge potential under such climate conditions [44]. The balance between the positive and negative effects of service crops regarding water use in the Mediterranean climate remains therefore to be quantitatively assessed over short- to long-term periods. This would require more field experiments with service crops and water balance measurements, combined with long-term simulation studies with improved crop models able to simulate a range of non-crop species under varying climatic and soil conditions [45].

To take advantage of synergies between service crops and climate change adaptation, management is key. Several authors recommend being agile in terms of sowing and destruction dates to adjust service crops’ water use and reduction of soil evaporation according to the actual drought conditions and cash crop development stages. In this perspective, techniques and tools are to be developed to regulate service crops’ biomass [38] and ensure the desired water-use dynamics. Finally, service crop selection is an essential aspect that requires further work. The choice of service crop species or mixtures based on their functional traits, especially belowground traits, appears to be one relevant approach to design eco-hydrologically performant service crops [46] that are both drought-resilient and drought-facilitative for the main crops. As for trees in agroforestry, exploring local plant biodiversity should be promising [47].

3. Landscape diversification
The term landscape is polysemic and can be ambiguous depending on the context of the study and on the scientific domain. We make our own the definition of Marshall [48], that defines the agricultural landscape as ‘a mosaic of farmers’ fields, semi-natural habitats, human infrastructures (e.g., roads) and occasional natural habitats’ (Figure 2). In what follows, we propose that adapting MA to water scarcity can be achieved through two approaches at the landscape level: 1) diversifying crops and agricultural management practices, and 2) implementing small-scales water harvesting infrastructures. These measures come to increase the heterogeneity of two main properties of landscape. Firstly, the composition that refers to the number and proportion of land-use category and, for agricultural lands, to the number and abundance of crops and agricultural practices; secondly the configuration that refers to the physical distribution and spatial characteristics of land uses, crops and agricultural practices [49]. Landscape diversification involves actually complexifying both composition and configuration [50].

Crop and agricultural practices. We argue that considering the composition and configuration of the landscape in terms of crops and agricultural management practices is a means to adapt agricultural systems to water scarcity. Reasoning involves selecting the appropriate crops and agricultural management practices at the right location in the landscape and time, taking into account the spatio-temporal variability of water fluxes and soil water. This reasoning aims to strike a balance between crop water requirements and soil water availability. Nelson and Burchfield [51] did observe that landscapes with increased complexity across various pedo-climatic conditions in the United States are generally more productive. They also found that crop yields were more influenced by compositional complexity rather than configurational complexity. However, there is currently no direct evidence in the literature linking crop production to landscape diversification under water-scarce conditions. Nonetheless, pieces of evidence have to be found in the correlations, reported in
many different climatic and agricultural regions, between crop yield and topographic position  
within agricultural landscapes [52, 53, 54, 55]. For instance, Ajami et al. [54] observed, in a  
climatic context similar to the Mediterranean one, that wheat yield ranged from 5.7 to 15.8 ton/ha  
depending on hillslope position (i.e., shoulder, back-, foot-, and toe-slope). The correlations can  
vary from year to year depending on weather conditions, and from region to region depending on  
the hydrological, edaphic and climatic conditions [53, 54]. The spatial structure of crop yield in  
relation to topography reveals that crop water use efficiency varies spatially as a result of i) the  
spatial heterogeneity of soil properties (texture, depth, organic matter content,...) due partly to long  
term soil redistribution by water erosion [56] (Lagacherie et al., 2018), ii) the spatial variability of  
soil water content as a result of hydrological processes (infiltration, runoff, subsurface flow,  
evapotranspiration) [57, 58] and iii) the local climate conditions controlled by elevation and  
exposure, among others [59]. Landscape diversification would aim at reaching the optimal  
combination in space and time of crops, cultivars and agricultural practices regarding crop yields.  
Landscape diversification is expected to optimize combinations of measures such as for instance  
reducing plant density, encouraging the cultivation of drought-resistant crops or varieties in  
landscape areas with soil prone to drier conditions, conducting soil tillage during the rainy season to  
enhance water infiltration, or selecting water-demanding crops in areas of water flow convergence  
and deep soil. This requires consequently a sound understanding of the soil variability, the  
hydrological cycle and the microclimate variability within the landscape.

Water Harvesting Infrastructures (WHI)

Small-scale WHI encompasses various linear structures, including terraces, hedgerows, earth bunds  
and stone barriers [60]. These structures are primarily constructed along topographic contour lines  
within fields or along field borders (Figure 2). Their purpose is to intercept and facilitate the local
infiltration of runoff water into the soil. Additionally, WHI also includes small reservoirs such as check dams, farm ponds and hillslope reservoirs, which supply water to irrigated plots [61, 62]. They capture runoff, store water and may refill shallow aquifers, thus increasing water availability for crops. Most of WHI are also referred to as water conservation systems. Implementing WHI substantially increases crop yields. From a meta-analysis of WHI effects [61], Bouma et al. reported an average 78% increase in crop yields, with larger values in low rainfall years, but with a great variability depending on the study. In addition to increasing yields, the WHI can enhance crop production by helping farmers to convert fallow lands into productive agricultural land [63]. The WHI in Mediterranean regions have always been considered as relevant techniques toward resilient agricultural landscapes facing water scarcity. However, the hydrological functioning of WHI at both local and landscape extents, as well as the impacts of WHI on local crop production, still remain major scientific challenges to be tackled, prior to designing efficient networks of infrastructures within landscapes for the management of water scarcity and crop water demand.

Designing sustainable Mediterranean landscapes

Agroecosystem modeling can complement field experiments (1) by scaling up impacts from local (field biodiversification, water harvesting infrastructures) to landscape levels and (2) by numerically exploring ex-ante landscape scenarios with varying crop diversification and water harvesting infrastructures [64]. Designing resilient and sustainable Mediterranean landscapes requires agroecosystem models that holistically represent at the landscape level the interactions between crop growth and development, management practices and water circulation, in relation to cropping systems and water harvesting infrastructures. Such models have also to consider soil and climate local variability. The primary shortcomings of current models lie in their failure to integrate the relevant spatial resolution and extent that encompass these interactions. Specifically, these include
the field scale, where crops and agricultural practices are implemented, the scale of water harvesting infrastructures, and the hydrological compartments (aquifer, hillslope, river) that govern water circulation within the landscape. While certain models strive towards achieving such integrative agroecosystem modeling and addressing these aforementioned shortcomings [65], the design of such models continues to present a scientific challenge in the future and overcoming these shortcomings.
Figure 2: Two typical Mediterranean landscapes. The different elements of landscapes are delineated with colored lines. The two images show how configuration and composition shape a landscape. On top, the landscape located in the south of France is composed mainly of vineyard fields, terraces, ditches, hedgerows and a stream. At bottom, the landscape located in north-east Tunisia is composed of tilled fields for annual crops, semi-natural areas and a wadi (ephemeral stream).

4. Conclusion

Improving the sustainability of Mediterranean rainfed agriculture in a context of water scarcity and climate change can be achieved through crop diversification at the field level by considering agroforestry, intercropping and service crops. Diversification of landscape by rearranging the composition and configuration of crops, as well as through landscape water harvesting infrastructures, can also help to achieve this goal. Diversification, at the field and landscape level, can provide food and livelihoods, but also ecosystem services (pest control, nutrient provision, carbon sequestration, soil preservation). In this review, we enlighten the scientific issues concerning each of the diversification modes. Nevertheless, the adaptation of Mediterranean Agriculture to water scarcity will not be achieved by mobilizing only one of these solutions, but by combining in space and time these solutions at both levels. New tools that consider the spatial and temporal
variability of Mediterranean landscapes, such as agro-hydrological models, are needed to evaluate such combinations. Landscape management will also require innovative governance based on new institutions and organizations involving the different stakeholders (farmers, water managers, land managers...) who are central actors for acceptability. Finally, the ability of Mediterranean agrosystems to evolve towards biodiversification is also contingent upon the social, cultural, and environmental contexts. Indeed, these agrosystems are typified by potential obstacles to achieving successful transition towards biodiversification, including limited market opportunities for some crops, insufficient availability of new crop varieties, equipment constraints and gaps in farmers' knowledge regarding cultivation of new varieties. Although the impact of such contextual factors on transition towards biodiversification has been explored in European and North American countries, it remains an issue for Mediterranean regions.

Acknowledgements

The ideas enlightened in this review originate partly in the research and exchanges undergone within the LMI NAILA (Franco-Tunisian laboratory of agricultural water management in rural landscapes). We thank all the colleagues of LMI NAILA for the fruitful collaborations. Financial, material and human support to LMI NAILA by IRD (French National Research Institute for Sustainable Development), by IRESA (Tunisian institution of agronomic research and higher education) and by the MESRS (Ministry of Higher Education and Scientific Research) have been much appreciated. We also thank Yves Martin-Prevel and Eric Verger, who lead the IRD transdisciplinary research community on sustainable food systems (CoSav SyAD), for inviting and encouraging us to produce this review.
References


*Burgess AJ, Cano MEC, Parkes B: The deployment of intercropping and agroforestry as
This paper provides an interesting review of the role of intercropping and agroforestry as an adaptation method towards climate change. It shows when and why multiple cropping systems can maximise water use efficiency and reduce the risk associated with crop loss through drought.


[27] Bayala J, Prieto I: Water acquisition, sharing and redistribution by roots: applications to


[40] Novara A, Cerda A, Barone E, Gristina L: Review Cover crop management and water...

This review highlights the significance of service crops in the Mediterranean region, with a specific focus on olive and vineyard. The key contribution of this review lies in providing quantifications of the benefits of service crops in analyzing runoff control and soil water content. It shows the contrasted benefits of service crop depending on climate conditions.


[44] Plaza-Bonilla D., Nolot JM, Raffaillac D, Justes E. Cover crops mitigate nitrate leaching in cropping systems including grain legumes: field evidence and model simulations. Agriculture Ecosystems Environment, 2015, 212 1-12. https://doi.org/10.1016/j.agee.2015.06.014


[46] Garcia L, Metay A, Kazakou E, Storkey J, Gary C, Damour G. Optimizing the choice of


**This study analyzes the relationship between landscape configuration and composition and agricultural production. Specifically, the study uses a national database with a diversity of landscapes, cropping systems and climate. It shows that in the United States, landscape composition, more than configuration, controls crop yields.**


*The study evaluates the spatial variability of wheat production in the landscapes of a subhumid Iranian province and analyzes the statistical relationships between crop yields, soil properties and topographic attributes. One of the interests of this work is to show that topographic indices explain the spatial variability of wheat yield, indicating the effect of spatial distribution of soil moisture content during the wheat production process in the study area.


[57] Du X, Jian J, Du C, Stewart RC: Conservation management decreases surface runoff and

https://doi.org/10.1016/j.iswcr.2021.08.001.


* Three paired scaling-up initiatives are compared in terms of the benefits of landscape-based interventions over individual plot-level interventions in three Indian semi-arid watersheds. Interestingly, the study shows how landscape-based interventions (earthen field bunds, farm ponds, check dams) resulted in a higher crop production per year due to conversion of fallow lands to croplands.
