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Jérôme Molénat, Karim Barkaoui, Salah Benyoussef, Insaf Mekki, Rim
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1 **Title** Diversification from field to landscape to adapt Mediterranean rainfed
2 agriculture to water scarcity in climate change context

3

4 **Authors**

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

7

8 **Affiliations**

9 (1) LISAH, University of Montpellier, INRAE, IRD, Institut Agro Montpellier, AgroParisTech,
10 Montpellier, France

11 (2) CIRAD, UMR ABSys, F-34398 Montpellier, France

12 ABSys, University of Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro,
13 Montpellier, France

14 (3) CIRAD, UMR AMAP, F-34398 Montpellier, France

15 AMAP, University of Montpellier, CIRAD, CNRS, INRAE, IRD, Montpellier, France

16 (4) INRAT, University of Carthage, Ariana, Tunisia

17 (5) INRGREF, University of Carthage, Ariana, Tunisia

18

19 *Corresponding author jerome.molenat@inrae.fr

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21

22 **Highlights**

23

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

29

30 **Keywords**

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

33

34 **Abstract**

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

44 hydrological models, useful to evaluate several spatiotemporal combinations of these solutions in
45 order to optimize soil water availability and crop water use.

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47

48 **1. Introduction**

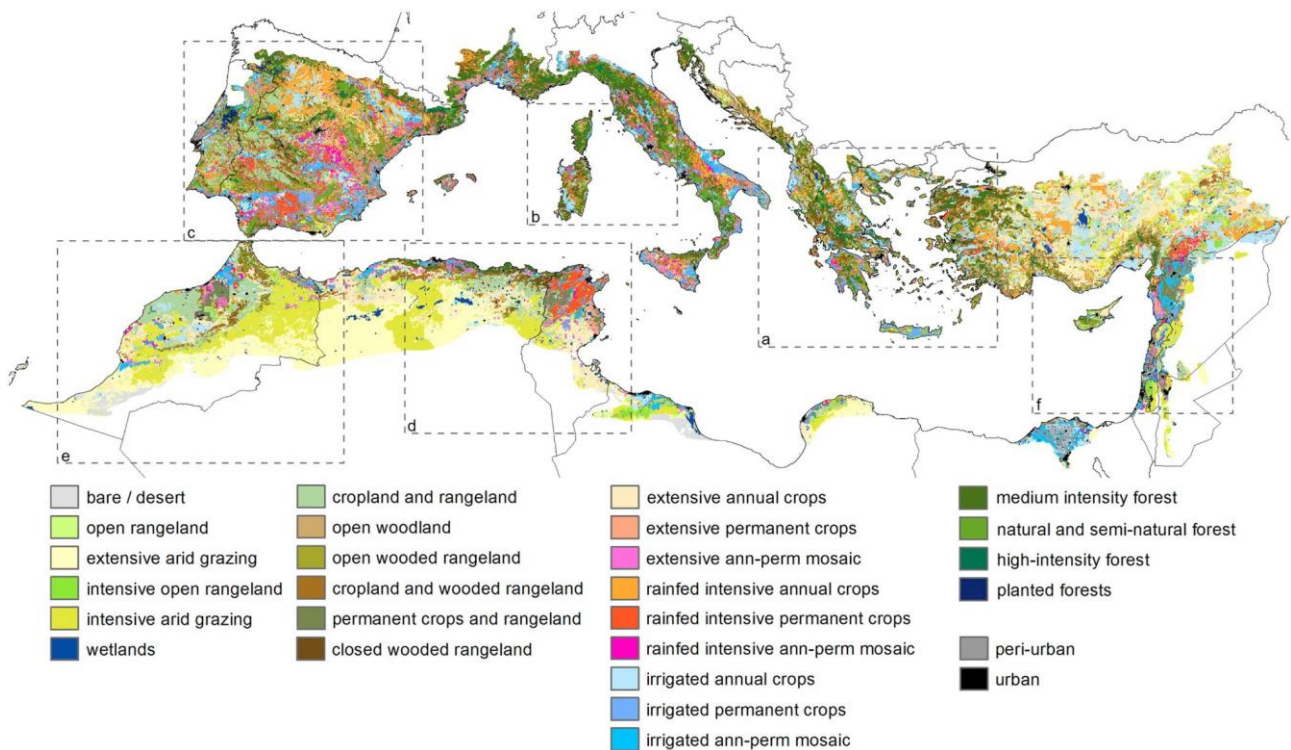
49 Mediterranean agriculture (MA) has developed over the millennia by benefiting from mild to hot
50 temperatures and adequate insolation. The population has shaped a very heterogeneous biophysical
51 environment (soil, topography, biodiversity) by designing landscapes and agricultural practices
52 adapted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

59 Climate change accentuates for MA the challenge of maintaining or even increasing production to
60 feed a growing population, while simultaneously preserving natural resources such as soil, water,
61 and biodiversity that are vulnerable to climate hazards and anthropogenic pressures. This also
62 requires addressing potential yield gaps that may exist. Climate projections show that average
63 temperatures will increase from 0.5° to 5.6°C, depending on the scenario, and that rainfall will
64 continue to decrease from April to September, by about 4% per °C of global warming [4].
65 Sustainable management of the scarce water resource in a warmer and drier climate is one of the
66 most crucial issues facing MA. Based on climate projections and crop modeling, water and heat
67 waves are, and will continue to be, key limiting factors for crop production [4]. The sustainability of
68 the Mediterranean food system will therefore depend on the sustainability of MA in a context of
69 water scarcity.

70

71 Adapting MA to water scarcity has already been extensively studied in the field of irrigation,
72 including new irrigation practices and technologies. Alternative water resources such as the reuse of
73 treated wastewater and desalinated water have also been increasingly used [4]. However, new
74 margins of progress also exist for Mediterranean rainfed agriculture in the framework of the agro-
75 ecological transition, to optimize the use of rainfall for agricultural production. Based on recent
76 literature, we aim to demonstrate the potential of diversification, considered at two distinct spatial
77 levels, in facilitating the adaptation of MA to water scarcity. Firstly, at the field level,
78 diversification can be achieved through practices such as intercropping, agroforestry, and service
79 crops. Secondly, at the landscape level, diversification involves diversifying crops and agricultural
80 management practices both in terms of their number, abundance and spatial organization, as well as
81 building small-scale water harvesting infrastructures with optimal density and topology.

82



84 **Figure 1:** Map of agricultural Mediterranean regions showing the main type of crops [5].

85

86

87 **2. Field diversification**

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

106

107 **Intercropping**

108 Intercropping or polyculture is defined as the cultivation of two or more different crop species
109 simultaneously in the same field during a growing season. In the Mediterranean, intercropping is an
110 ancient practice consisting of mixtures of grain or fodder cereals (e.g., barley, durum wheat) and
111 legumes (e.g., chickpea, fava bean), and to a lesser extent, of other arable crops. Intercropping has
112 recently gained increased interest due to its potential to increase climate resilience of agriculture
113 [11], and its well-demonstrated advantage over monocultures in terms of resource efficiency, crop
114 yield [12], quality [13], stability [14], and provision of ecosystem services [15].

115 Several mechanisms are involved in regulating water balance in intercrops as compared to
116 sole crops. When water is a limiting factor to crop production, intercropping can increase crop
117 water uptake and water use efficiency through physiological and ecological mechanisms and
118 optimize the overall soil moisture environment for crops [14]. Better water use efficiency is
119 generally attributed to better water uptake in the soil profile, resulting from the exploitation of
120 denser root systems and complementary spatial root distribution of both intercrop components
121 species [17, 18], and to the delay between species in reaching their maximum water requirement.
122 For instance, in cereal-legume mixtures, the capacity of cereals to use water from deep soil layers
123 when they reach their flowering stage allows associated legumes to use water from shallow layers
124 while they are at their grain-filling stage, limiting water competition during sensitive stages for
125 grain production of both species [19]. Moreover, increased dry matter accumulation rate and
126 reduced water loss through soil evaporation and transpiration and runoff are conducive to better
127 water utilization [20].

128 However, the choice of crop species and varieties, sowing densities and spatial arrangements
129 are critical to finding the right mix achieving the expected positive outcomes from intercropping.
130 For instance, the lack of complementarity for water can strongly limit yield advantages [21]. A

131 better understanding of processes underlying crop competition, complementarity, cooperation and
132 compensation regarding water use under future dry conditions will be essential to manage and
133 predict crop growth, water use efficiency, and yield formation in Mediterranean intercropping
134 systems. Crop modeling has the potential to address such issues, but would require further
135 development before being used for intercropping design purposes, mainly because they have been
136 used for sole crops and therefore processes relevant to intercropping like plant competition and
137 plasticity have been only rarely coded so far which could promote complementarity among
138 associated crops [22].

139

140 **Agroforestry**

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

148 Regarding the water cycle, trees act positively on multiple above- and below- ground
149 ecohydrological processes, and they offer the opportunity to preserve water and improve the water
150 balance at the field level. Trees can regulate the local microclimate by providing shade, thus
151 reducing evapotranspiration [10], limiting water loss through soil evaporation, and preventing crops
152 from severe water stress under drought [26]. By digging deep, trees can use water from deep soil
153 reserves usually not accessible to arable crops, making the overall water harvesting more complete,
154 and limiting water and nutrient losses through deep drainage. In addition, trees with deep roots can

155 activate several water redistribution mechanisms. They can lift water from deep soil layers up to the
156 upper layers through a process known as hydraulic lift and potentially act as ‘bio-irrigators’ for the
157 underlying crops [27]. In semiarid areas with less than 450 mm of rainfall, hydraulic lift was
158 estimated to provide up to an additional 35-47 mm of water annually, representing around 10% of
159 the total precipitation [28]. By creating alliances with soil microorganisms, trees can facilitate the
160 use of water and nutrients under dry conditions [29]. As a result, AFS were shown to support higher
161 land- and water productivities than monocultures under Mediterranean or semiarid conditions, as
162 recently illustrated by an increase in total productivity of 10-44% in olive- [30], walnut- [31], apple-
163 [32], apricot- [33], jujube- [34] based agroforestry. They also help mitigate the effect of increasing
164 drought on ecosystem services in more extensive pastures [35].

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

179 heterogeneity within fields to promote the overall complementarity and facilitative effects of trees
180 in AFS.

181

182 **Service crops**

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

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

200 However, drawbacks specific to water-limited regions need to be accounted for when

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

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

221

222

223 **3. Landscape diversification**

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

236

237 Crop and agricultural practices. We argue that considering the composition and configuration of the
238 landscape in terms of crops and agricultural management practices is a means to adapt agricultural
239 systems to water scarcity. Reasoning involves selecting the appropriate crops and agricultural
240 management practices at the right location in the landscape and time, taking into account the spatio-
241 temporal variability of water fluxes and soil water. This reasoning aims to strike a balance between
242 crop water requirements and soil water availability. Nelson and Burchfield [51] did observe that
243 landscapes with increased complexity across various pedo-climatic conditions in the United States
244 are generally more productive. They also found that crop yields were more influenced by
245 compositional complexity rather than configurational complexity. However, there is currently no
246 direct evidence in the literature linking crop production to landscape diversification under water-
247 scarce conditions. Nonetheless, pieces of evidence have to be found in the correlations, reported in

248 many different climatic and agricultural regions, between crop yield and topographic position
249 within agricultural landscapes [52, 53, 54, 55]. For instance, Ajami et al. [54] observed, in a
250 climatic context similar to the Mediterranean one, that wheat yield ranged from 5.7 to 15.8 ton/ha
251 depending on hillslope position (i.e., shoulder, back-, foot-, and toe-slope). The correlations can
252 vary from year to year depending on weather conditions, and from region to region depending on
253 the hydrological, edaphic and climatic conditions [53, 54]. The spatial structure of crop yield in
254 relation to topography reveals that crop water use efficiency varies spatially as a result of i) the
255 spatial heterogeneity of soil properties (texture, depth, organic matter content,...) due partly to long
256 term soil redistribution by water erosion [56] (Lagacherie et al., 2018), ii) the spatial variability of
257 soil water content as a result of hydrological processes (infiltration, runoff, subsurface flow,
258 evapotranspiration) [57, 58] and iii) the local climate conditions controlled by elevation and
259 exposure, among others [59]. Landscape diversification would aim at reaching the optimal
260 combination in space and time of crops, cultivars and agricultural practices regarding crop yields.
261 Landscape diversification is expected to optimize combinations of measures such as for instance
262 reducing plant density, encouraging the cultivation of drought-resistant crops or varieties in
263 landscape areas with soil prone to drier conditions, conducting soil tillage during the rainy season to
264 enhance water infiltration, or selecting water-demanding crops in areas of water flow convergence
265 and deep soil. This requires consequently a sound understanding of the soil variability, the
266 hydrological cycle and the microclimate variability within the landscape.

267

268 **Water Harvesting Infrastructures (WHI)**

269 Small-scale WHI encompasses various linear structures, including terraces, hedgerows, earth bunds
270 and stone barriers [60]. These structures are primarily constructed along topographic contour lines
271 within fields or along field borders (Figure 2). Their purpose is to intercept and facilitate the local

272 infiltration of runoff water into the soil. Additionally, WHI also includes small reservoirs such as
273 check dams, farm ponds and hillslope reservoirs, which supply water to irrigated plots [61, 62].
274 They capture runoff, store water and may refill shallow aquifers, thus increasing water availability
275 for crops. Most of WHI are also referred to as water conservation systems. Implementing WHI
276 substantially increases crop yields. From a meta-analysis of WHI effects [61], Bouma et al. reported
277 an average 78% increase in crop yields, with larger values in low rainfall years, but with a great
278 variability depending on the study. In addition to increasing yields, the WHI can enhance crop
279 production by helping farmers to convert fallow lands into productive agricultural land [63]. The
280 WHI in Mediterranean regions have always been considered as relevant techniques toward resilient
281 agricultural landscapes facing water scarcity. However, the hydrological functioning of WHI at both
282 local and landscape extents, as well as the impacts of WHI on local crop production, still remain
283 major scientific challenges to be tackled, prior to designing efficient networks of infrastructures
284 within landscapes for the management of water scarcity and crop water demand.

285

286 **Designing sustainable Mediterranean landscapes**

287 Agroecosystem modeling can complement field experiments (1) by scaling up impacts from local
288 (field biodiversification, water harvesting infrastructures) to landscape levels and (2) by numerically
289 exploring ex-ante landscape scenarios with varying crop diversification and water harvesting
290 infrastructures [64]. Designing resilient and sustainable Mediterranean landscapes requires
291 agroecosystem models that holistically represent at the landscape level the interactions between
292 crop growth and development, management practices and water circulation, in relation to cropping
293 systems and water harvesting infrastructures. Such models have also to consider soil and climate
294 local variability. The primary shortcomings of current models lie in their failure to integrate the
295 relevant spatial resolution and extent that encompass these interactions. Specifically, these include

296 the field scale, where crops and agricultural practices are implemented, the scale of water harvesting
297 infrastructures, and the hydrological compartments (aquifer, hillslope, river) that govern water
298 circulation within the landscape. While certain models strive towards achieving such integrative
299 agroecosystem modeling and addressing these aforementioned shortcomings [65], the design of
300 such models continues to present a scientific challenge in the future and overcoming these
301 shortcomings

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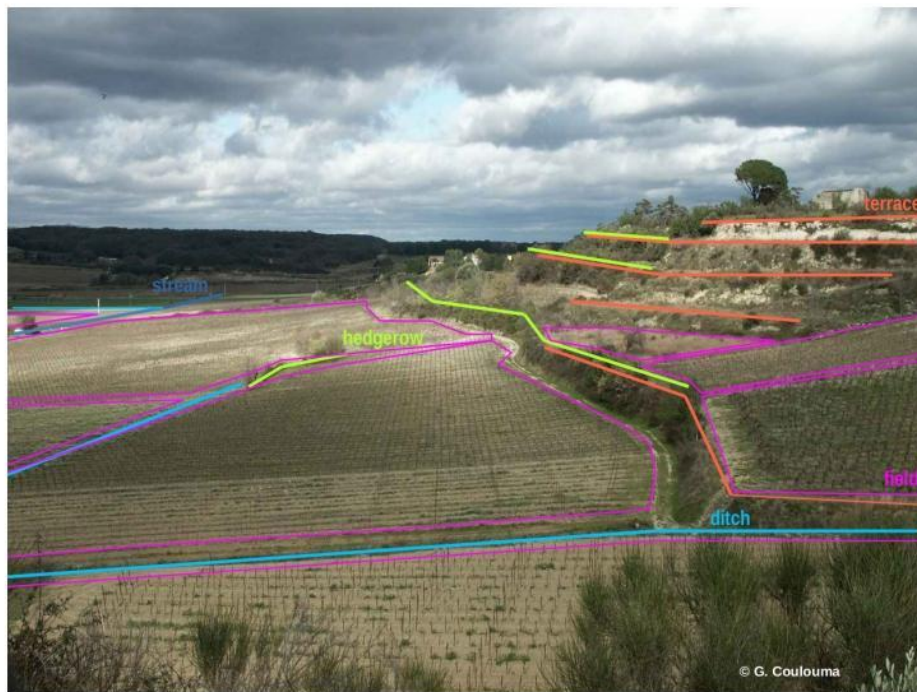
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324 **Figure 2:** Two typical Mediterranean landscapes. The different elements of landscapes are
325 delineated with colored lines. The two images show how configuration and composition shape a
326 landscape. On top, the landscape located in the south of France is composed mainly of vineyard
327 fields, terraces, ditches, hedgerows and a stream. At bottom, the landscape located in north-east
328 Tunisia is composed of tilled fields for annual crops, semi-natural areas and a wadi (ephemeral
329 stream).

330

331 **4. Conclusion**

332 Improving the sustainability of Mediterranean rainfed agriculture in a context of water scarcity and
333 climate change can be achieved through crop diversification at the field level by considering
334 agroforestry, intercropping and service crops. Diversification of landscape by rearranging the
335 composition and configuration of crops, as well as through landscape water harvesting
336 infrastructures, can also help to achieve this goal. Diversification, at the field and landscape level,
337 can provide food and livelihoods, but also ecosystem services (pest control, nutrient provision,
338 carbon sequestration, soil preservation). In this review, we enlighten the scientific issues concerning
339 each of the diversification modes. Nevertheless, the adaptation of Mediterranean Agriculture to
340 water scarcity will not be achieved by mobilizing only one of these solutions, but by combining in
341 space and time these solutions at both levels. New tools that consider the spatial and temporal

342 variability of Mediterranean landscapes, such as agro-hydrological models, are needed to evaluate
343 such combinations. Landscape management will also require innovative governance based on new
344 institutions and organizations involving the different stakeholders (farmers, water managers, land
345 managers...) who are central actors for acceptability. Finally, the ability of Mediterranean
346 agrosystems to evolve towards biodiversification is also contingent upon the social, cultural, and
347 environmental contexts. Indeed, these agrosystems are typified by potential obstacles to achieving
348 successful transition towards biodiversification, including limited market opportunities for some
349 crops, insufficient availability of new crop varieties, equipment constraints and gaps in farmers'
350 knowledge regarding cultivation of new varieties. Although the impact of such contextual factors on
351 transition towards biodiversification has been explored in European and North American countries,
352 it remains an issue for Mediterranean regions.

353

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364

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