Original Research Article

Effects of climate and weeds on the establishment of thyme-based living mulch systems in drylands of Cyprus

Abstract

Mulching systems are at the spotlight of sustainable soil management as nature-based solutions for combating desertification.

Aims: We tested how living mulch systems based on rainfed *Thymbracapitata*(L.) Cav., can be established under different pressure from drought and weedsin dryland carob plantations.

Study design:10 thyme plots in semi-aridclimate;11 plotsin arid climate; different weed competition intensity(60 thyme per plot).

Place and Durations of the Study: South-eastern Cyprus, betweenDecember 2019 and 2022.

Methodology: Survival and soil cover for 1260 *T. capitata*seedlings (3-5 cm tall, 16 seedlings per m^2) was assessed at the end of 3 dry seasons (d.s.) together with weed community composition, weed abundance (w.a.) and biomass. Climate data andDe Martone’s Aridity Index (DMAI) were used to assess drought severity.

Results: Around 80%of the thymes survivedat the end of the first d.s, that followed a very rainy year (ca. 600 mm annual precipitation; P; ca. +50% than normal;ca. 19 DMAI).Thyme survival appeared unaffected byw.a.in both sites. After a severe drought that occurred the second year (ca. 300 mm P; ca. -22% than normal; ca. 9.5 DMAI)thyme survival rates dropped at the end of the d.s.to ca. 20%at the site with 3 times higher w.a. and biomass(mostly from *Avena* sp.).However, they were unaffected under loww.a.creating a 29% soil cover (vs.7% in VRY). These results remainedtill the end of the third d.s.

Conclusions: To combatdesertification and drought intensification under climatic change, rainfed *T. capitata*as living mulch appears unaffected by weeds during wet orvery dry years under low w.a. However, under highw.a., a weed management systemis requiredif climate is arid.

Keywords:nature-based solutions, living mulch, weeds, Mediterranean, dryland, climate change

1. Introduction

Aridity, which is increasing worldwide because of climate change, affects the structure and functioning of dryland ecosystems (Berdugo et al., 2020). Drylands cover 41% of the Earth’s surface.The sustainable management of these soils is critical as they are particularly susceptible to desertification (IUCN, 2019). The increase in dryland expansion rate will likely lead to drylands covering half of the global land surface by the end of this century (Huang et al., 2015). One example is the Mediterranean region and its agroecosystems which are considered particularly vulnerable to drought (Aguilera et al., 2020).

Average temperatures in this region are predicted to increase by 20 percent, precipitation to decline between 4-22 percent and droughts are expected to be 5-10 times more frequent (MedECC, 2020). These conditions will likely increase irrigation requirements between 4 and 18% (Aguilera et al., 2020), while negatively impacting the quality and yield of agricultural crops (MedECC, 2020). Thus, strict management of water resources, along with the restoration of soils and vegetation to reduce ecosystem vulnerability, are urgently needed both in the Mediterranean region and globally to address current and future desertification challenges (Huang et al., 2015).

Intensive agricultural practices can lead to degradation of crucial regulating and supporting ecosystem services (Palm et al., 2014) and can adversely impact soil’s crucial physicochemical properties, such as its aggregate stability and organic content (Paul et al., 2013). At the same time these practices can speed up soil erosion thousand times faster than natural processes (Montanarella et al., 2015), while reducing microbial activity.Nature-based solutions,on the other hand, focus on enhancing long-term ecosystem services to address socio-economic and environmental challenges such as described above, while reducing dependence on non-renewable resources (Maes and Jacobs, 2017). Regenerative, low-input agricultural methods, such as reduced tillage and the establishment of living and dry mulching systems, are nature-based solutions known to increase carbon sequestration, enhance biodiversity, facilitate nutrient cycling, prevent soil erosion and increase water infiltration and availability(Palm et al., 2014).

Under rainfed conditions, mulching permits the mitigation of soil temperature extremes, soil moisture retention, weed control and promotion of soil productivity (Pramanik et al., 2015). Dry organic mulching can be applied using different organic materials, such as crop residue (straw and grass clippings), woodchips, sawdust and compost among others(Safari et al., 2021; Mohiuddin et al., 2020). Living mulches are cover crops interplanted or undersown with a main crop. Advantages of living mulches over dead cover crops may include increased weed suppression, reduced erosion and leaching, better soil health, and greater resource-use efficiency (Bhaskar et al., 2021).Over synthetic mulches,living mulches may enhance agroecosystem biodiversity and suitability for a wider range of cropping systems (Bhaskar et al., 2021). Incorporating aromatic plants into tree-based agroforestry systems as living mulch, has the potential to increase commercial value (Rao et al., 2004), increase soil organic matter and water content (Zhang et al., 2021) and improve soil health and crop performance(Steenwerth and Guerra, 2012).Furthermore, a multifunctional agroecosystem based on living mulch could be upscaled to represent a nature-based solution that can provide enhanced socioeconomic in addition to its environmental benefits (Maes and Jacobs, 2017).These above are top priorities for making dryland agroecosystems more sustainable under climatic change.

Thymbra capitata[(L.) Cav.], [synonym of *Thymus capitatus* (L.) Hoffmanns. et Link.] is an aromatic plantadapted to extreme drought stressfound in the thermo-Mediterranean vegetation belt. It is typical of garrigue or phrygana vegetation.*T. capitata* makes very conservative use of soil moisture (Moradi et al., 2014)enabling it to grow on marginal and saline soils(Cordovilla et al., 2014).Such properties make it an ideal candidateas a living mulch for dryland agroforestry systems,as competition with the tree crop is likely to be low.However,*T. capitata,* despite being drought adapted, is also a slow growing plant. The latter makes it vulnerable to competition from fast growing weeds.

This paper is the first to evaluate the establishment potential of living mulch systems based on *T. capitata*(Thyme system)under rainfed conditions in drylands,as a nature-based solution for sustainable soil management under climate change.Our analysis spanned over a duration of three years and covered the effects of very wet, normal as well as very dry years in arid and semi-arid conditions of Mediterranean climate. The influence of a changing climate was tested together with different competition from weeds to determine under which combination of climate type and weed pressure can the Thyme system become successfully established.

2.Materials and Methods

2.1 Experimental sites

The field experiments were conducted under rainfed conditions in a carob agroforestry systems planted at 7 m distance between trees and between tree rows (7x7 m planting density: 204 trees / ha) in two sites of different edaphological and climatic conditions on the island of Cyprus in the southeast Mediterranean. They lasted from winter 2019 (December) till winter 2022 (December) (Fig.1). The first site included two neighboring agricultural plots located in Skarinou (SKR), Larnaca district [(i) 34°48'37.68"N 33°21'20.57"E, (ii) 34°48'40.75"N 33°21'14.62"E] at 189 m average elevation. The second site was situated in Vrysoulles (VRY), Ammochostos district (35°04'42.2"N 33°52'46.7"E) at 32 m elevation. Both regions are classified as prone to desertification (Fig.1; see also *Climate data* section). At the SKR site 20-year-old carob trees were selected. Since planting they had been drip irrigated at the base of their stem during the dry months up to summer 2019. Thereafter, irrigation stopped so as not to affect the experiments. At the VRY site 18-years old carobs were selected that had only been irrigated during the first two years of establishment. Prior to the experiment, conventional soil and weed management in both locations was performed with 3 to 4 ploughing applications every year depending on seasonal rainfall and growth of weeds.

The soil at SKR site is classified as calcaric-lithic-Leptosols (65% carbonate) with a pH of 7.84 and 3.43% organic matter (Table 1). The soil at VRY site is classified as calcaric-leptic-Regosols dominated by red clay (24% carbonate) with a pH of 7.93 and 1.59% organic matter (Table 1). Soil analysis was performed at the Agricultural Research Institute of Cyprus.

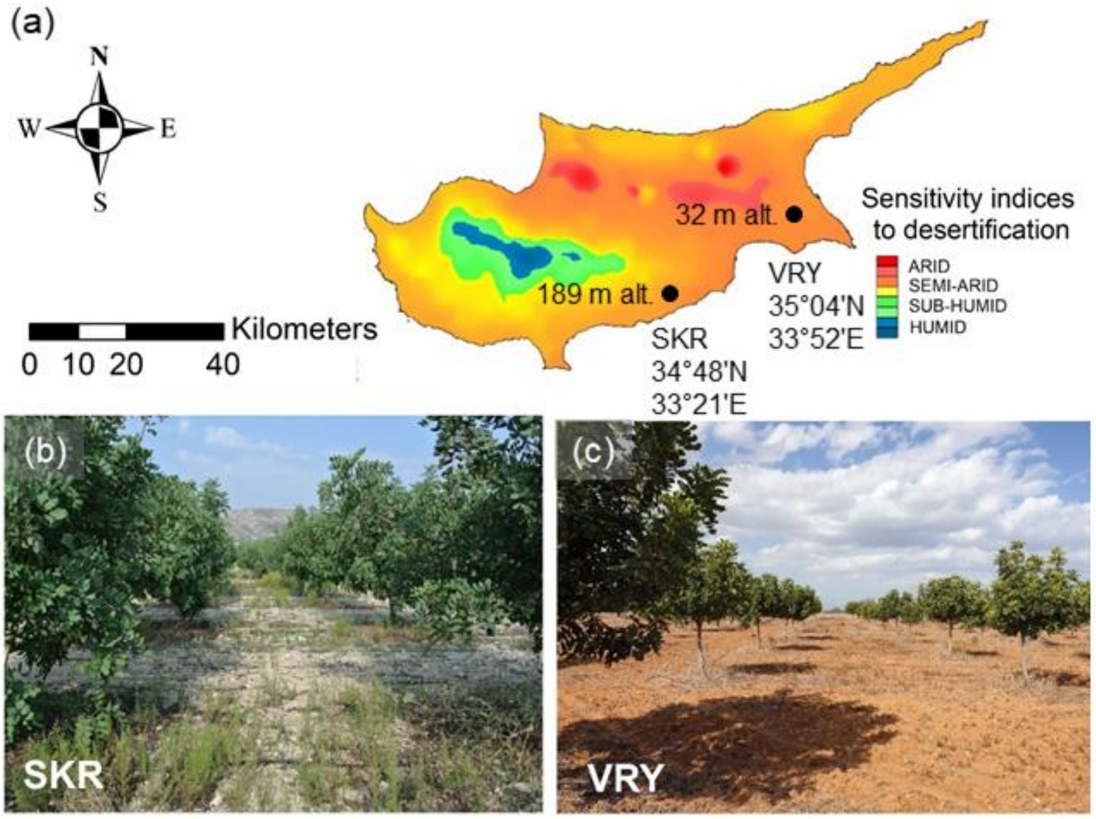


Fig.1 (a) Location of the two experimental sites in Cyprus, Skarinou (SKR; b) and Vrysoulles (VRY; c) within carob agroforestry systems in regions prone to desertification (the highest desertification risk is for arid, the lowest for humid areas; SKR semi-arid; VRY arid; IACO 2007) with calcareous soil in SKR and red clay soil in VRY. Altitude (alt.)

Table 1. Soil properties of the two experimental sites, SKR and VRY prior to the establishment of experimental plots (Autumn 2019).

Soil Property	**Site**		**Method applied**
	SKR	**VRY**	
Total nitrogen (%)	0.15	0.12	CHN elemental analyzer
Total nitrogen (Kjeldhal) (%)	0.23	0.16	Kjeldahl (Kirk, 1950)
Available phosphorus (ppm)	18.20	11.33	Olsen (Pierzynski, 2000)
Exchangeable potassium (ppm)	179	333	
Calcium carbonate (CaCO3) (%)	65.2	24.2	Bernard calcimeter (ASTM, 2014)
Conductivity (μS/cm)	609	502	
Organic carbon (%)	1.99	0.92	CHN elemental analyzer
Organic matter (%)	3.43	1.59	
pH	7.84	7.93	
Soil classification	calcaric-lithic-Leptosols	calcaric-leptic-Regosols	
Textural classification	Silty clay	Silty clay loam	Bouyoucos Hydrometer (Huluka and Miller, 2014)

2.2 Experimental design

The experimental layout covered a ca. 3 x 1.2 m surface plotper tree with 60 thymes (ca. 3-5 cm tall)planted at the sun exposed side of each treeca. 1.5 m away from the trunk (no shading from the tree on the thymes)at a density of ca. 16 seedlings per m^2,in late December 2019 till early January 2020 (Fig.2), and thyme systems (1260 *T. capiata*in 21 plots; 10 plots in SKR with lower weed abundance; 11 plots in VRY higher weed abundance (Fig. 2). No weeding took place in the plots throughout the duration of the experiment.

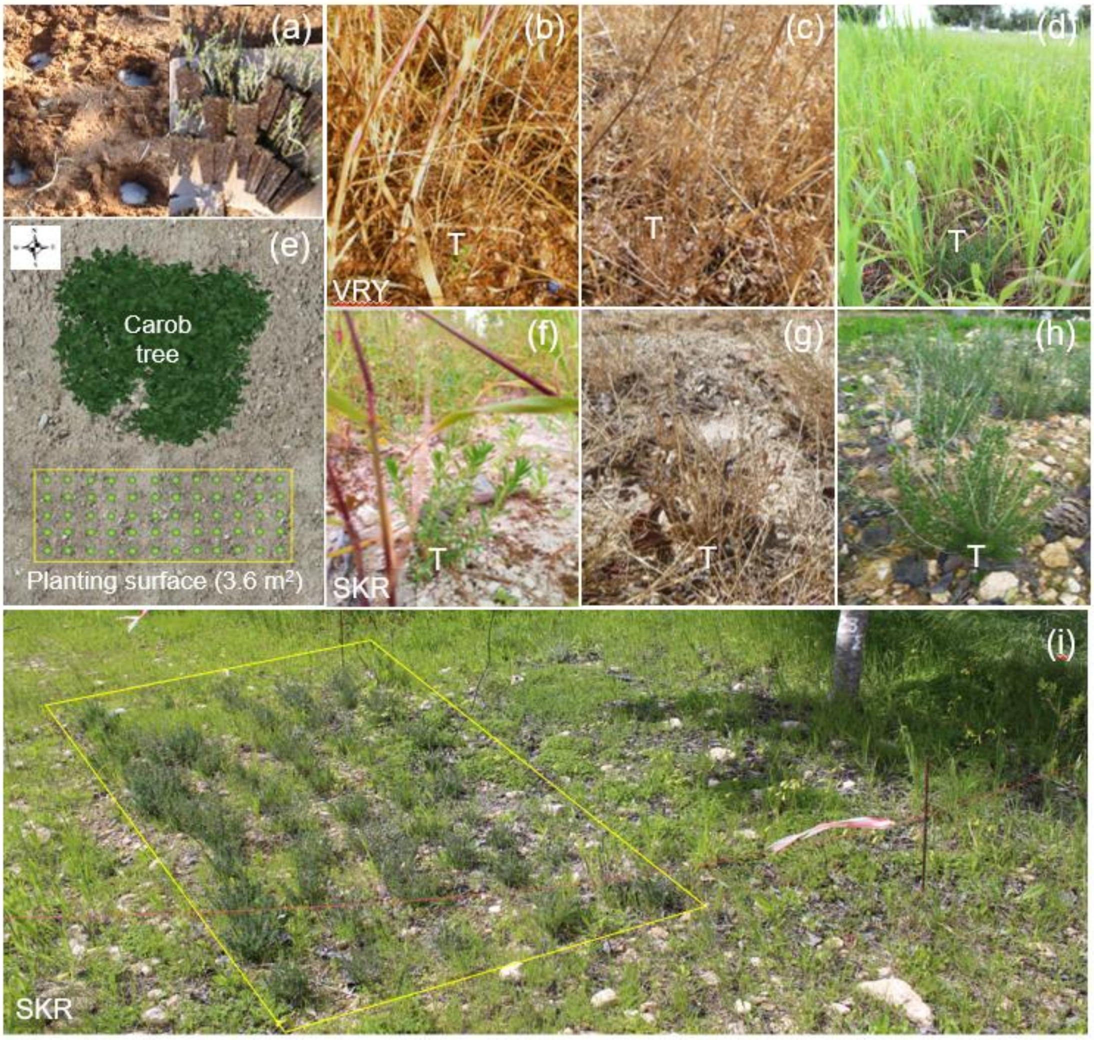


Fig 2. (a) Establishment of *T. capitata* (ca. 3-5 cm tall seedlings) as living mulch supported by ecologically engineered soil (Thyme system), (e) 60 thymes per plot (green dots) were installed at the sun exposed side of selected carob trees at sites of higher (b-d; VRY) and lower (f-h; SKR;) weed abundance. T = thyme. (b, f) April-May 2020, (c, g) October 2021, (d, h, i) March 2022.

To determine the pressure from completion weeds exercised on the Thyme system in each site, weed composition and abundance as well as weed biomass were assessed. Assessment was performed using 32 quadrats of 1 m^2randomly placed on unmanaged wild vegetation within SKR and VRY sites, not more than 2 m away from carob trees (weed plots). 20 weed plots (8 plots for SKR, 12 for VRYin May 2020) were used to assess plant composition and abundance and 12 plots (4 plots for SKR, 8 for VRYin June 2020) to assess weed biomass. This design permitted to independently test weed abundance from weed biomass. If our weed plots were correctly selected as representative of weed conditions within the sites, then any differences in weed abundancebetween SKR and VRY sites, would also need to be reflected as weed biomass differences. Indeed, this was found to be the case (see Results).

To potentially provide additional support to thymes for water and nutrient uptake under rainfed conditions, their soil was ecologically engineered by installing in each thyme planting hole 5 gr of attapulgite, a water absorbing porous granular clay (0.25-1.18 mm granules; AGLEV® SI 200 GEOHELLAS). Together, 5 gr of Micosat-F Olivo (CCS) microgranular complex of beneficial microbes were added, slightly mixed with the soil at the bottom of the hole (Fig. 2). The aim was to utilize the synergy of arbuscular mycorrhizal fungi, plant growth promoting rhizosphere bacteria and saprophytic fungi with a mineral that could provide more space, water and nutrients for these microbes grow. Mycorrhizal fungi consisted of *Glomus coronatum* GO 01, *Glomus viscosum* GC 41 and *Glomus intraradices* GB 67 strains, while bacteria of *Pseudomonas* sp., *Bacillus subtilis* BA 41, *Streptomyces* sp. SA 51, saprotrophic fungi (*Trichoderma* sp., *Trichoderma viride* TV 03, *Trichoderma harzianum* TH 01), and yeast (*Picia pastoris*). The above ecological soil engineering method is reported for the first time.

2.3 Thyme survival rate and soil cover estimation

All living thymes (baring green leaves) were counted in each Thyme system plot and the thyme survival rate was estimated as the percentage of living thymes compared to the total number of thymes planted during establishment. Thyme survival rate was estimated three times during the duration of the experiment (February 2021, May 2022 and December 2022), covering the recovery from the dry seasons of 2020, 2021 and 2022.

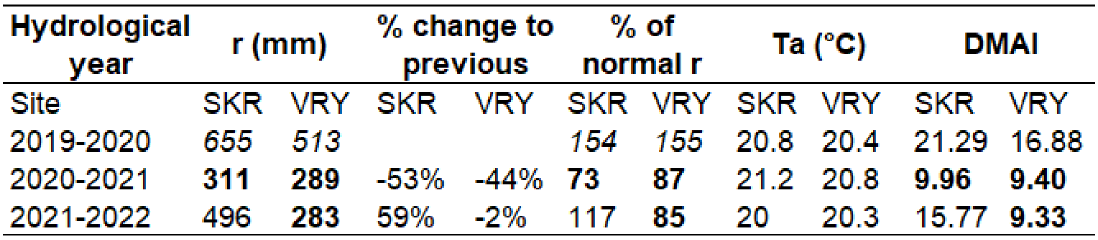
Thyme cover was assessed following the second dry season during the third year of experiment (May 2022) by measuring the canopy of all thyme plants within a 1 m^2 quadrat for each of the Thyme system plots in each site location. To estimate the soil covered by thyme canopy per plant, the distance between thyme branches furthest extending from the central stem was measured (D1) as well as the distance perpendicular to D1 (D2), were used for calculating the total surface of thyme canopy projected on the soil based on the equation: Thyme soil cover per plant = $\pi * D1 * D2 / 4$.

2.4 Climate data

Both areas are classified as dryland sites with a semi-arid (SKR) and an arid climate (VRY) (Interwies and Görlitz, 2012; Katsanos et al., 2016; Zittis et al., 2020; Table 2; Fig. S2) experiencing a long dry season (rainfall below 5mm/month for the 5-6 hottest months during the years studied). Normal rainfall for the hydrological year (Oct-Sep; 1981-2010) is 425 mm for SKR and 331 mm for VRY (Cyprus Department of Meteorology). Climate data were used from the three meteorological stations closest to SKR and VRY sites belonging to the network of the Cyprus Department of Meteorology located within a distance smaller than 5km from each experimental site, namely Skarinou (station number: 628, 34°49'17.22", 33°21'19.45"), Dipotamos (station number: 633, 34°51'08.24", 33°21'40.47"), and Frenaros (station number: 1845, 35°02'32.64", 33°55'03.414") stations at 180, 175 and 78 m elevation respectively. For 2022, due to missing data in Dipotamos station, temperature data for SKR site was estimated based on regression analysis (R^2 = 0.997) using temperature data from the closest station (ca. 2 Km distance from Dipotamos station, namely Kakoratzia station; number: 1634, 34°51'40.55", 33°22'57.10", at 231 m elevation).

As a measure of climatic dryness the De Martonne's Aridity Index (DMAI) was calculated i.e. DMAI = r / (Ta + 10), (Leech, 2013) where r = total annual precipitation (mm) and Ta = annual mean temperature (°C) within the hydrological year (Oct-Sep) (Table 2). A DMAI below 10 signifies arid conditions (Leech, 2013). Such hydrological years occurred in 2020-21 and 2021-2022 for VRY site, while SKR reached a marginal DMAI of 10 in 2020-21. The year 2019-20 was a very wet year in both sites, although again SKR had wetter conditions compared to VRY (r=655 mm vs. 513 mm; DMAI= 21.3 vs. 16.9; Table 2).

Table 2. Annual climate data for SKR and VRY by hydrological year (Oct-Sep). De Martonne's Aridity Index = DMAI, r = rainfall in bold/italics for below/above the 1981-2010 mean, Ta = mean temperature.



Hydrological year	**r (mm)**		**% change to previous**		**% of normal r**		**Ta (°C)**		**DMAI**	
Site	SKR	VRY	SKR	VRY	SKR	VRY	SKR	VRY	SKR	VRY
2019-2020	*655*	*513*			*154*	*155*	20.8	20.4	21.29	16.88
2020-2021	**311**	**289**	-53%	-44%	**73**	**87**	21.2	20.8	**9.96**	**9.40**
2021-2022	496	**283**	59%	-2%	117	**85**	20	20.3	15.77	**9.33**

2.5 Statistical analysis

To test for normality of the data sets the One-Sample Kolmogorov-Smirnov Test was used. Since data were found to be non-normally distributed, the Kruskal-Wallis test was appliedand medians were used in analysis. The means and standard error were also calculated and given as an additional reference. The level of significance used was set at *P*<0.05. All statistical analysis was carried out using SPSS Statistics 27 (SPSS, Chicago, IL, USA).

3. Results

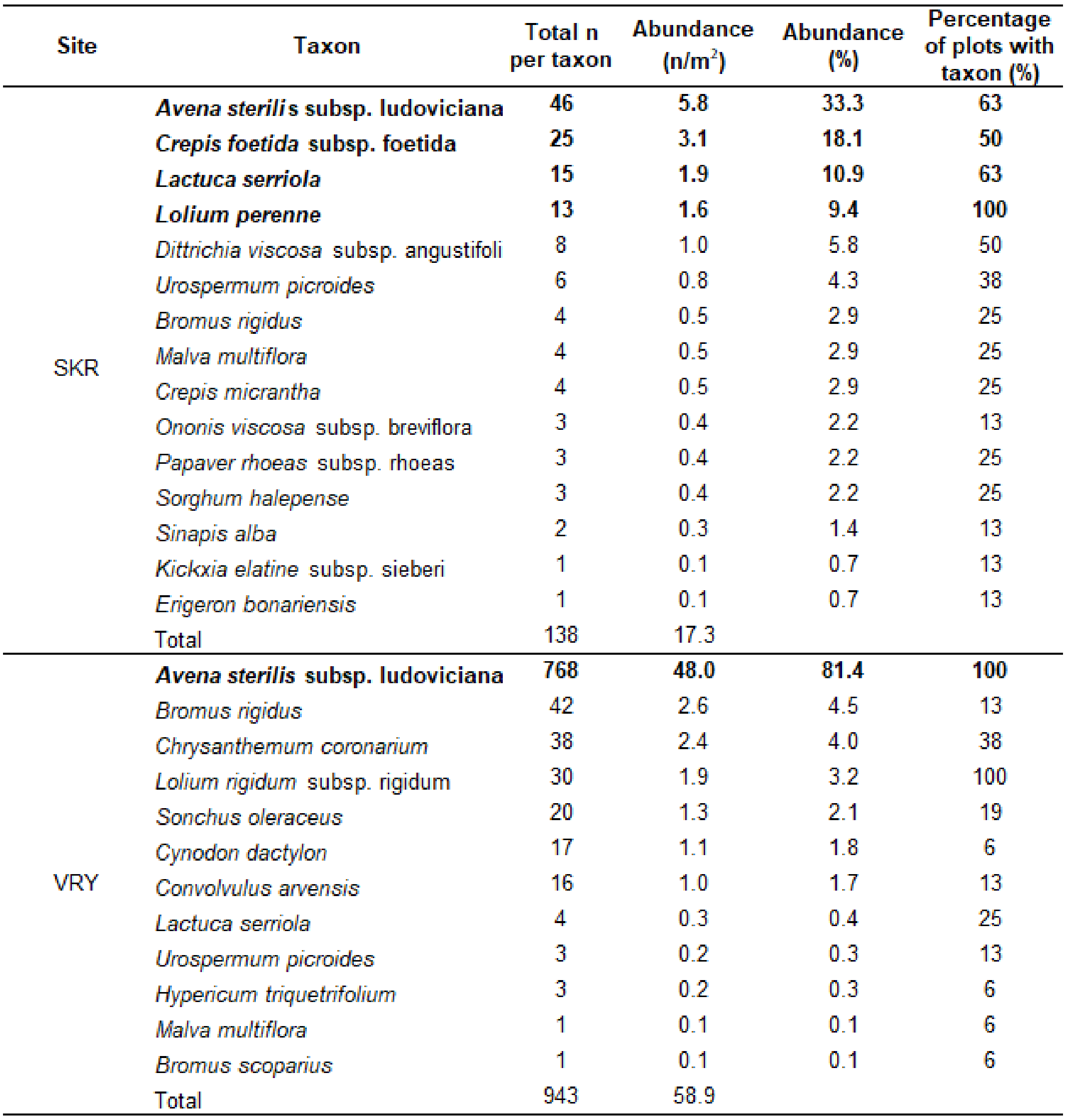
3.1 Climate assessment

Our experiment spanned over a three-year monitoring period offering sufficient climatic variability to assess the optimal conditions for the establishment of the *Thyme system* under rainfed conditions. SKR site was classified as having a semi-arid climate under normal conditions (Table 2). However, plants in SKR experienced very wet conditions during the hydrological year 2019-20 (+54% than normal rainfall; 655 mm annual rainfall, De Martone Aridity Index; DMAI= 21.3), very dry climate in 2020-21 (-27% than normal rainfall; 311mm annual rainfall, DMAI= 9.96) creating arid conditions for the particular year. Average climate conditions occurred in 2021-22 (+17% than normal rainfall; 490mm annual rainfall, DMAI= 15.8). Climate at the otherwise arid site of VRY was likewise very wet during the hydrological year 2019-20 (+55% than normal rainfall; 513 mm annual rainfall, DMAI= 16.9), but arid for the two years that followed (2020-21; -13% than normal; 289 mm, DMAI= 9.4; and 2021-22; -15% than normal; 283 mm, DMAI= 9.3; Table 2).

3.2 Weed assessment

From the floristic analysis of weed plots, 15 weed taxa were identified in SKR and 12 in VRY with only 4 taxa in common (Table 3). The dominant taxa in SKR (above 10% plant population abundance; p. ab.) were *Avena sterilis* subsp. *ludoviciana*with p. ab. of 33.3 % and presence in 63% of the sampled plots, *Crepisfoetida* subsp. *foetida*with p. ab. of 18.1 % and presence in 50% of the sampled plots, followed by *Lactucaserriola*(p. ab. of 10.9 % and presence in 63% of the sampled plots) and *Lolium perenne*(p. ab. of 9.4 % and presence in 100% of the sampled plots). On the other hand, site VRY was dominated by only one taxon i.e. *Avena sterilis* subsp. *ludoviciana*with p. ab. of 81.4 % and presence in 100% of the sampled plots (Table 3).Plant abundance (number of plants per m^2)was 17.3 in SKR and 58.9 in VRY, meaning that weeds were 3.4 times more abundant in VRY than in SKR (P<.001; Fig. 3). These finding were also reflected in results from the weed biomass plots, which produced 2.7 times higher plant biomass in VRY than SKR (P< .05; Fig. 3).

Table 3. Weed taxa and their abundance. In bold the species with abundance above 10% (considering the total n of plants per m^2). n= number of plants.



Site	Taxon	Total n per taxon	Abundance (n/m^2)	Abundance (%)	Percentage of plots with taxon (%)
SKR	***Avena sterilis* subsp. ludoviciana**	**46**	**5.8**	**33.3**	**63**
	***Crepis foetida* subsp. foetida**	**25**	**3.1**	**18.1**	**50**
	Lactuca serriola	**15**	**1.9**	**10.9**	**63**
	Lolium perenne	**13**	**1.6**	**9.4**	**100**
	Dittrichia viscosa subsp. angustifoli	8	1.0	5.8	50
	Urospermum picroides	6	0.8	4.3	38
	Bromus rigidus	4	0.5	2.9	25
	Malva multiflora	4	0.5	2.9	25
	Crepis micrantha	4	0.5	2.9	25
	Ononis viscosa subsp. breviflora	3	0.4	2.2	13
	Papaver rhoeas subsp. rhoeas	3	0.4	2.2	25
	Sorghum halepense	3	0.4	2.2	25
	Sinapis alba	2	0.3	1.4	13
	Kickxia elatine subsp. sieberi	1	0.1	0.7	13
	Erigeron bonariensis	1	0.1	0.7	13
	Total	138	17.3		
VRY	***Avena sterilis* subsp. ludoviciana**	**768**	**48.0**	**81.4**	**100**
	Bromus rigidus	42	2.6	4.5	13
	Chrysanthemum coronarium	38	2.4	4.0	38
	Lolium rigidum subsp. rigidum	30	1.9	3.2	100
	Sonchus oleraceus	20	1.3	2.1	19
	Cynodon dactylon	17	1.1	1.8	6
	Convolvulus arvensis	16	1.0	1.7	13
	Lactuca serriola	4	0.3	0.4	25
	Urospermum picroides	3	0.2	0.3	13
	Hypericum triquetrifolium	3	0.2	0.3	6
	Malva multiflora	1	0.1	0.1	6
	Bromus scoparius	1	0.1	0.1	6
	Total	943	58.9		

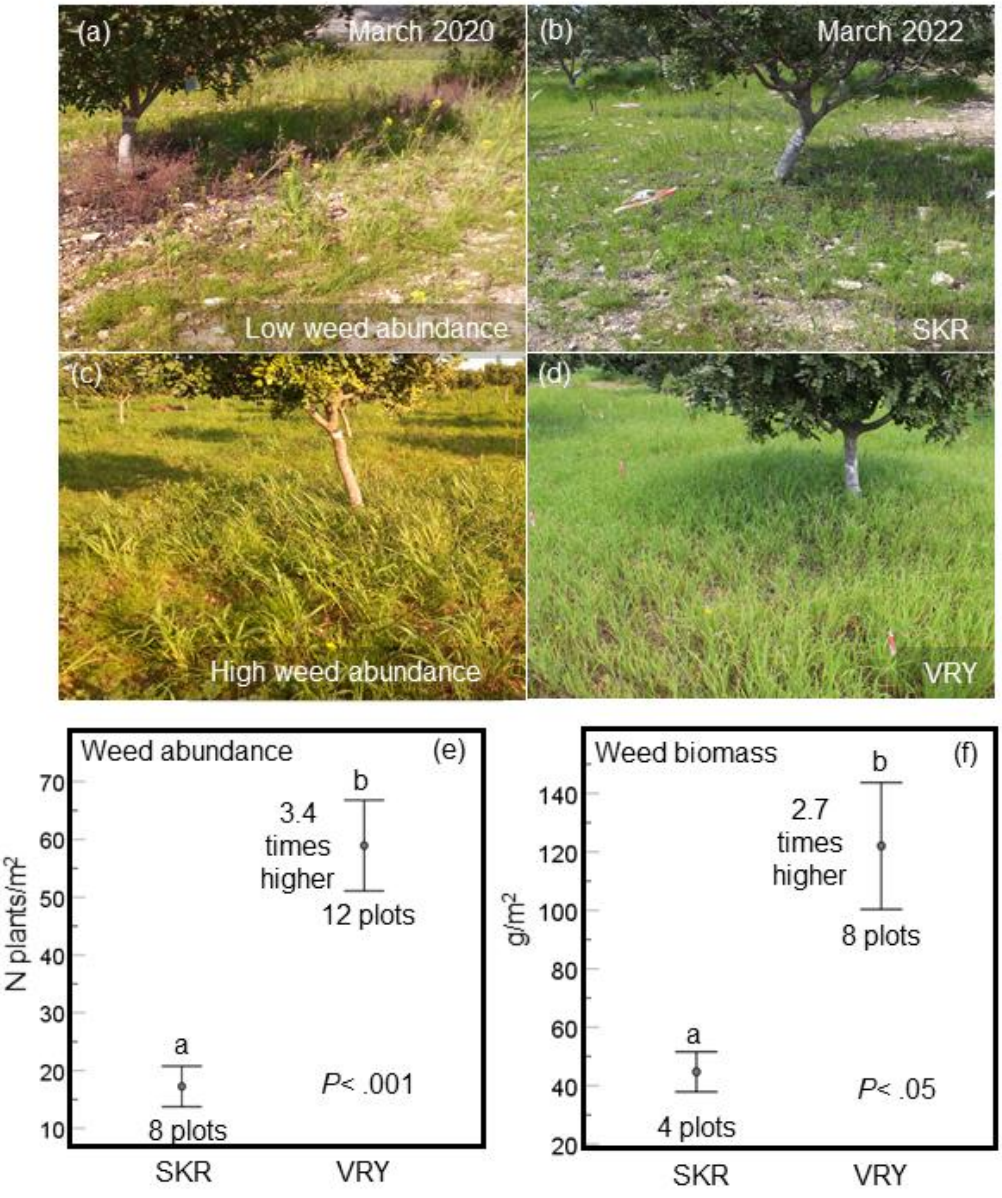


Fig 3. (a, b) Weed conditions in SKR (semi-arid) and (c, d) VRY (arid) sites. (e) Weed abundance and (f) biomass differences per experimental site (N=number). Different letters signify statistically significant differences

3.3 Thyme survival rates

After the first dry season of the wet climatic year 2019-20, thyme survival rates were estimated at 72% (median) in the arid site with higher weed abundance (VRY) and almost reached 90% (median) in the semi-arid site with lower weed pressure (SKR). These differences were not found to be statistically significant (*P* = 0.76; SKR; Fig. 4). However, during the dry climatic year of 2020-21 that followed, recorded thyme survival at the end of the dry season significantly dropped to 20% (median) in the arid site with higher weed abundance, representing a soil cover of 8%. Nevertheless, in the semi-arid site with lower weed pressure (SKR) thyme survival remained above 80% (median; significantly different to VRY site at *P*<.001).Thymes reached a soil cover of 29% (4.4 st. error), despite the very dry year experienced at the particular site creating arid conditions (DMAI=9.96; Table 2), vs. 7% soil cover (1.1 st. error) at VRY. The ca. 60% difference (*P*<.001) in thyme survival rates between the two sites was retained during the third year as well. After three dry seasons, thyme survival stabilized at ca. 20% (median) at the arid site. Nonetheless, it still remained at ca. 80% in the semi-arid site with lower weed pressure (Fig. 4).

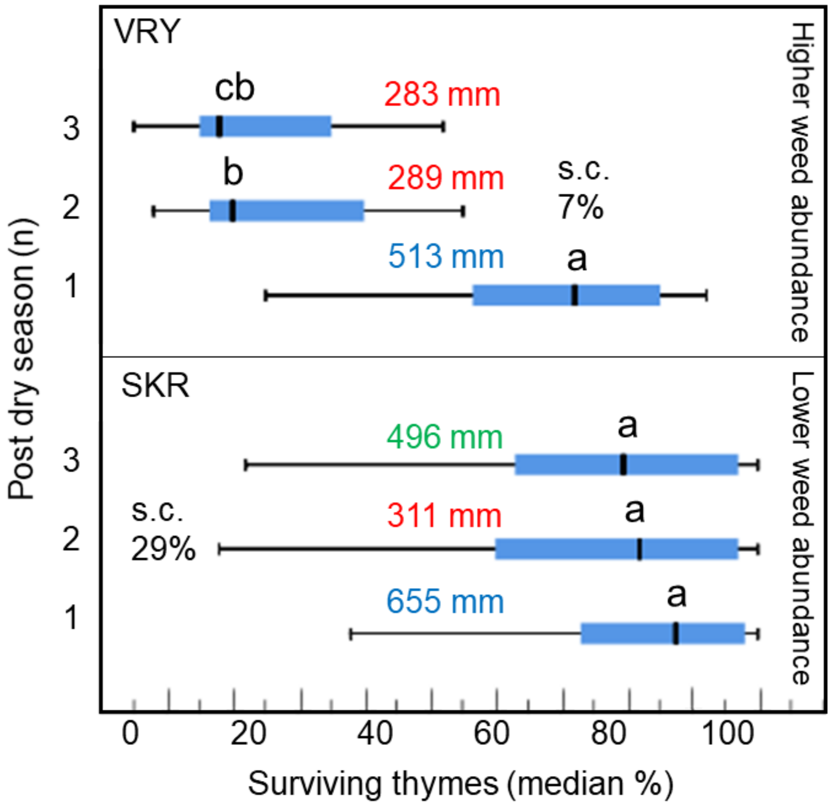


Fig. 4 Thyme survival (% of median) at each end of 3 dry seasons (d. s.). Precipitation for very dry hydrological yearsin red, very wet years in blue and normal conditions in green (see Table 2). a-b and a-c statistically different at *P*<.001.s.c. = soil cover at the end of the 2rd d. s.The 60% decline in thyme survival significantonly at the arid site with higher weed abundance (VRY) during very dry years.

4. Discussion

The Thyme system achieved high rates of establishment (ranging between ca. 70% to 90%) in both low and high weed abundance sites during the circumstantially very wet hydrological year that coincided with year one of experiments. Therefore, if the first year of the Thyme system’s establishment is dry, irrigation in wintertime may be considered, in order to replicate the conditions experienced by thyme plants in our experiments. Under such very wet climate conditions (first year of tests; + ca. 54-55% or ca. 185-205 mm more rainfall than normal) *Avena sterilis* does not significantly affect thyme survival when rainfall of the hydrological year reaches above 500 mm (DMAI>16.5; Fig. 3 and 4; Table 3).

Our findingsalso provide insight into the limits of the Thyme system proposed. If the first year of the Thyme system’s establishment is dry, irrigation in wintertime may be considered, so as to replicate the conditions experienced by thymes in our experiments. Under such very wet climate conditions(first year of tests; + ca. 45-55% or ca. 185-205 mm more rainfall than normal), thyme survival rates reached 70% even at the site with higher weed completion (VRY; Fig 4). This suggests that grass weeds alone (mostly *Avena* sp.) do not significantly affect thyme survival when rainfall of the hydrological year reaches above 500 mm (DMAI>16; Table 2).

During the very dry year that followed, rainfall was reduced by 344 mm or by 53% in SKR and 224 mm or by 44% in VRY compared to the previous year

(Table 2). Despite drought affecting both sites, thyme survival was retained at high levels (ca. 80%) only at SKR, the site with low weed abundance (Fig. 3 and 4). This result was achieved despite climate shifting there to arid for the particular year (DMAI =9.96; Leech, 2013; Table 2). Apparently, the higher weed abundance at VRY site, with *Avena sterilis* dominating (Table 3), most likely drove thyme survival to ca. 20%, a decline by 50% compared to the previous year.Thus, under conditions when rainfall fell below 300 mm (DMAI< 9.5) the Thyme system cannot efficiently compete with *Avena sterillis*, which thrives as a weed on the red clay soils of the region.

*A.sterilis*is among the most challenging weed species found to be growing in the Southern Mediterranean (Castellanos-Frías et al., 2014; Karkanis et al., 2016). Wild vegetation, acting most likely as the second driver influencing *T. capitata* establishment, exercised ca. 3 times higher competition pressure on the Thyme systems of VRY compared to SKR (Fig. 3). Weeds have been observed to almost always have an adverse effect on main crop yields (Mahajan and Chauhan, 2021; Qasem, 2021) reducing available soil moisture (Harris et al., 2004). Therefore, to establish the Thyme system under arid conditions management of grass weeds is required to reduce competition for soil moisture. Towards this goal grazing by goats or other herbivores could be tested during dry years in spring as a nature based solution, if these animals are proven to show preference to grass weeds instead of thyme.

Vulnerability to climate change depends not only on overall climatic variability but also on the occurrence of extreme events (Dorman et al., 2015). As more regions are expected to become affected by climate change, the need for adaptation to drought and climatic extremes becomes imperative for agroecosystems in the global effort to combat desertification. The severe drought conditions that thymes experienced during the second year of establishment fall within the upper rainfall reduction range projected for regions of the Mediterranean towards the second half of the 21rst Century as a result of global warming (MedECC, 2020). This observation suggests that Thyme systems installed in semi-arid regions with low weed completion may be considered sustainable even under a future drier climate driven by climate change. Such living mulching systems, can better regulate soil moisture and temperature extremes compared to organic dry mulching (Iqbal et al., 2020; Safari et al., 2021). Furthermore, they can provide additional advantages for dryland agroforestry and other agricultural systems. For instance, living mulch: a) Does not require yearly application, saving labour, energy and other costs, b) Provides permanent soil cover, securing soil, c) Offers additional ecosystem services e.g. facilitates pollinators, promotes biodiversity and sequesters carbon, d) Can potentially support farmer income as a secondary crop.Thus, dryland agroforestry, could benefit from the Thyme system proposed in semi-arid calcareous regions threatened by desertification that fall within the *T. capitata* distribution range. Such regions cover almost the entire span of the Mediterranean (POWO, 2023).

5. Conclusions

In light of the urgent need for a transition towards more sustainable agricultural production, our findings provide insight into the application of a thyme based living mulch system as a nature-based solution. Such systems may promote agroforestry and agricultural systems able to provide multiple ecosystem services and potentially combat desertification phenomena in drylands under climatic change. *T. capitata*was established without irrigation at a rate of ca. 80% within semiarid agroforestry systems, when competition with fast growing weeds was low under both very wet and very dry climate extremes. However, under ca. 3 times higher weed competition and arid conditions the establishment rate stabilized at ca. 20% after 3 years.Thus, further research is required in identifying an optimum weed management system at sites with high weed abundance for the Thyme system to improve its establishment rates during arid years.

References

Aguilera E, Díaz-Gaona C, García-Laureano R, Reyes-Palomo C, Guzmán GI, Ortolani L, Sánchez-Rodríguez M, Rodríguez-Estévez V, 2020.Agroecology for adaptation to climate change and resource depletion in the Mediterranean region, A review. Agric. Syst. 181: 102809.

Berdugo M, Delgado-Baquerizo M, Soliveres S, Hernández-Clemente R, Zhao Y, Gaitán JJ, Gross N, Saiz H, Maire V, Lehman A, Rillig MC, Solé RV, Maestre FT, 2020. Global ecosystem thresholds driven by aridity, Science. 367: 787–790.

Bhaskar V, Westbrook A, Bellinder R, DiTommaso A,2021. Integrated management of living mulches for weed control: A review, Weed Technology 35(5): 856-868.

Castellanos-Frías E, García De Leõn D, Pujadas-Salva A, Dorado J, Gonzalez-Andujar JL, 2014. Potential distribution of *Avena sterilis* L. in Europe under climate change. Ann. Appl. Biol. 165: 53–61.

Cordovilla MP, Bueno M, Aparicio C, Urrestarazu M, 2014. Effects of Salinity and the Interaction Between *Thymus vulgaris* and *Lavandula angustifolia* on Growth Ethylene Production and Essential Oil Contents. J. Plant Nutr. 37: 875–888.

Dorman M, Perevolotsky A, Sarris D, Svoray T, 2015. Amount vs. temporal pattern : On the importance of intra-annual climatic conditions on tree growth in a dry environment. J. Arid. Environ. 118: 65–68.

Harris R, Clark J, Matheny N, 2004. Arboriculture: integrated management of landscape trees shrubs and vines 4th ed, Prentice Hall Inc Upper Saddle River.

Huang J, Yu H, Guan X, Wang G, Guo R, 2015.Accelerated dryland expansion under climate change. Nat. Clim. Chang. 6: 166–171.

IACO, 2007. Consultation Services for the Production of a National Action

Plan to Combat Desertification in Cyprus - Contract No, 3/2007 – Environment Service Executive Summary – Final Report.

Interwies, E., Görlitz, S., 2012. The role of water pricing and water allocation in agriculture in delivering sustainable water use in Europee–CASE STUDY CYPRUS. Annexes p.88

Iqbal R, Raza MAS, Valipour M, Saleem MF, Zaheer MS, Ahmad S, Toleikiene M, Haider I, Aslam MU, Nazar MA, 2020. Potential agricultural and environmental benefits of mulches—a review. Bull. Natl. Res. Cent. 44. https://doi.org/10.1186/s42269-020-00290-3

IUCN, 2019. Drylands and climate change. Issues Brief. International Union for Conservation of Nature and Natural Resources.Available from https://www.iucn.org/resources/issues-brief/drylands-and-climate-change.

Karkanis A, Travlos IS, Bilalis DJ, Tabaxi EI, 2016. Integrated weed management in winter cereals in Southern Europe in: Weed and Pest Control: Molecular Biology Practices and Environmental Impact, Nova

Katsanos, D., Retalis, A., Tymvios, F., Michaelides, S., 2016. Analysis of precipitation extremes based on satellite (CHIRPS) and in situ dataset over Cyprus. Nat. Hazards 83, 53–63. https://doi.org/10.1007/s11069-016-2335-8Science Publishers Inc. USA pp 1–15.

Larsson L, Båth A, 1996. Evaluation of soil temperature moderating and moisture conserving effects of various mulches during a growing season. Acta Agric. Scand. Sect. B Soil Plant Sci. 46: 153–160.

Leech G, 2013. Classification of Arid & Semi-Arid Areas: A Case Study in

Western Australia. https://doi.org/10.22459/aurj.05.2013.07

Maes J, Jacobs S, 2017. Nature-Based Solutions for Europe's Sustainable Development. Conserv. Lett. 10: 121–124.

Mahajan G, Chauhan BS, 2021. Interference of wild oat (*Avena fatua*) and sterile oat (*Avena sterilis* ssp.*ludoviciana*) in wheat, Weed Sci. 69: 485–491.

MedECC, 2020. Climate and Environmental Change in the Mediterranean Basin – Current Situation and Risks for the Future, First Mediterranean Assessment Report, Marseille France.

Montanarella L, Badraoui M, Chude V, Baptista Costa IDS, Mamo T, Yemefack M, Singh Aulakh M, Yagi K, Young Hong S, Vijarnsorn P, Zhang GL, 2015. Status of the world's soil resources. Main Report.

Moradi P, Ford-Lloyd B, Pritchard J, 2014. Plant-water responses of different medicinal plant thyme (*Thymus* spp.) species to drought stress condition. Aust. J. Crop Sci. 8: 666–673.

Palm C, Blanco-Canqui H, DeClerck F, Gatere L, Grace P, 2014. Conservation agriculture and ecosystem services: An overview. Agric. Ecosyst. Environ. 187: 87–105.

Paul BK, Vanlauwe B, Ayuke F, Gassner A, Hoogmoed M, Hurisso TT, Koala S, Lelei D, Ndabamenye T, Six J, Pulleman MM, 2013. Medium-term impact of tillage and residue management on soil aggregate stability soil carbon and crop productivity. Agric. Ecosyst. Environ. 164: 14–22.

POWO, 2023.*Thymbra capitata* (L.) Cav. Plants of the World Online, Kew

Sci.Available from: https://powo.science.kew.org/taxon/urn:lsid:ipni.org:names:460817-1#source-KBD.

Pramanik P, Bandyopadhyay KK, Bhaduri D, Bhattacharyya R, Aggarwal P,2015. Effect of mulch on soil thermal regimes - A review. Int. J. Agric. Environ. Biotechnol. 8: 645.

Qasem JR, 2021. Competition of weeds dominated by wild oat (*Avena sterilis* l,) in wheat (*Triticum durum* desf.) in Jordan, Agronomy 11, https://doi.org/10.3390/agronomy11091816

Rao MR, Palada MC, Becker BN, 2004. Medicinal and aromatic plants in agroforestry systems. In:P.K.R. Nair, M.R. Rao,L.E. Buck (Eds.) New Vistas in Agroforestry. Advances in Agroforestry vol 1, Springer, Dordrecht. pp 107–122.

Safari N, Kazemi F, 2016. Examining performances of organic and inorganic mulches and cover plants for sustainable green space development in arid cities. Desert 1: 65–75.

Safari N, Kazemi F, Tehrani A, 2021. Examining temperature and soil moisture contents of mulches in the urban landscaping of an arid region. Desert 26: 139–156.

Mohiuddin G, Debnath S, Maitra S, 2020. Mulching: Materials Advantages and Crop Production. In: S. Maitra,D.J. Gaikwad,S.Tanmoy (ed.) Protected Cultivation and Smart Agriculture.New Delhi Publishers, New Delhi. pp 55–66.

Steenwerth K, Guerra B, 2012. Influence of floor management technique on grapevine growth disease pressure and juice and wine composition: A review. Am. J. Enol. Vitic. 63: 149–164.

Zittis, G., Bruggeman, A., Camera, C., 2020. 21St Century Projections of Extreme Precipitation Indicators for Cyprus. Atmosphere. 11, 343. https://doi.org/10.3390/atmos11040343.

Zhang Y, Han M, Song M, Tian J, Song B, Hu Y, Zhang J, Yao Y, 2021. Intercropping With Aromatic Plants Increased the Soil Organic Matter Content and Changed the Microbial Community in a Pear Orchard. Front. Microbiol, 12: 1–15.