Deliverable 5.2

Report on the assessment water conservation and use by crops under different CA agricultural practices in Mediterranean countries

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Executive summary

This report summarizes the results obtained in the CAMA WP5 task 5.2. aimed to evaluating the impact of conservation agriculture (CA) on soil water conservation, water use and water use efficiency

The WP5 of the CAMA project has evaluated the impact of conservation agriculture on crop yield and some related variables as yield component and even grain protein content¡, but also in water productivity. The network of experiments with 10 scenarios (different edapho-climatic conditions) gives us a main assessment of the soil management system comparison (effect of reduction of tillage). Other factors as water regime, crop and varieties type, cropping system (crop rotation, intercropping), and fertilizer application.

The main conclusions obtained in this WP are:

In general reduced and no tillage systems promote a higher soil water conservation I the several scenarios developed. In Italy, a greater significant water use value in NT was observed for broad bean, while a greater WUE value for seed production for durum wheat in MT. In Greece experiments Crop Water Use Efficiency was similar for *Lathurys sativus* and for *Hordeum vulgare* grown under MT and CT during 2020-2021 and 2021-2022, respectively. In the period 2022-2023 where *Hordeum vulgare* was grown under MT and CT, water use (%) revealed higher values under conventional tillage along with higher yield compared to minimum tillage. The results suggest that increased attention should be paid to the choice of crops in the rotation when minimum tillage is applied. In Spain experiments, the results suggest after these three growing seasons, that reduction of till and No-tillage are adequate strategies for this Mediterranean area to maintain and increase the water use efficiency. Also, N fertilization should be adapted to the growing season and a higher dose of N fertilization did not increment this indicator. The best results are obtained under NT. In this study, the use of organic fertilizer obtained better yields making this option to reduce the use of synthetic fertilizers based on a more efficient use of the available water. The study carried out in Tunisia in the period encompassed three consecutive cropping seasons, with the 2022-23 season marked by severe drought conditions. Analysis of durum wheat Water Use Efficiency (WUE) revealed varying impacts of Rotation (R) and Tillage (T) practices. This highlights the importance of strategic rotation management to maximise conservation tillage benefits. In seasons with lower precipitation levels and prolonged dry periods, NT management enhanced water availability during critical growth stages, thereby increasing WUE compared to conventional tillage. The results underscore the potential of integrating NT practices with strategic crop rotation to optimize durum wheat WUE, especially in diverse and challenging climatic conditions. The principal findings in Algeria under the conditions of the case study (Setif región) make it possible to define relationships between WUE and NUE over a wide range of rain-fed and N-application conditions in semiarid regions These findings could be considered as the first simultaneous assessment of WUE and NUE by intercropped cereals and legumes.

1. Introduction

1.1. Scope of the document and objectives

This document presents the main results obtained in the activities performed on WP5 and Task 5.2. The main aim of WP5 was to assess the performance of conservation agriculture on crop yields, water conservation and crop water use in Mediterranean conditions. This general objective was divided among the next three specific objectives that match the four tasks of WP5:

- Assess the effect of short- and long-term CA on crop yield in different pedo-climatic conditions. (Task 5.1)
- Assess the effect of short- and long-term CA on water use and water use efficiency in different pedo-climatic conditions. (Task 5.2)
- Determine the effect of CA on water infiltration and available water for the crop. (Task 5.3)
- Predict variability of yields and water use efficiency under different management and climate scenarios in different agroecosystems, especially for smallholders using calibrated models. (Task 5.4.)

Therefore, the findings presented in Deliverable D 5.2 belong to the activities performed partly in Task 5.2

1.2. Notations, abbreviations and acronyms

CA	Conservation Agriculture
CAMA	Conservation Agriculture in the Mediterranean Area
CAP	Common Agricultural Policy
CDERP	communication, dissemination and exploitation of the results plan
EC	European Commission
IPR	Intellectual Property Rights
PMT	Project Management Team
RD&I	Research, Development and Innovation
RIA	Research and Innovation Action
TRL	Technological Readiness Level
WP	Work Package
WT	Work Task

1.3. Background

CA was developed in many areas around the world with successful adoption by farmers, however in Mediterranean areas still there is a limited expansion. Despite the Mediterranean basin has pedo-climatic conditions and traditional agriculture that make it a very suitable area for the adoption of CA, due to different reasons this adoption is still limited. Crop yield is one main reason for the adoption of crop technology. However, considering the limitations in water resources in the Mediterranean cropping systems, the assessment and improvement of the crop water productivity depending on the agricultural practices is important for the sustainability of the agricultural activity. Agriculture is the predominant user (75-80%) of the available freshwater resources mostly derived from rainfed soil moisture. The FAO predicts that agricultural water withdrawals will increase by approximately 14% during 2000-2030 to meet the food demand. An increase in the productivity of rainfed agriculture is possible using water accumulation and maintenance, reducing runoff and evaporation increasing water infiltration and retention, and improving WUE. At this stage, and to assist agricultural production systems, indicators such as water use and water use efficiency and those related to the water balance should be used to determine the viability of those cropping systems. Those indicators do not only show the use of resources such as water but also assess the agronomic and environmental performance of the proposed techniques and cropping systems development for farmers and also for smallholder sustainability. Under semiarid rainfed conditions, soil water storage increases with the use of CA systems which leave more crop residues on the soil surface. Moreover, this effect escalates as the degree of aridity of the site increases. Inversion tillage should be avoided in these conditions, especially in soils prone to crust formation, because it can have deleterious effects on infiltration, reducing their capacity to store water and leading to reduced crop yield. Mulching is an important component of conservation agriculture.

CA could be adopted in all diverse crops (field crops, orchards and even horticultural crops). The cropping system is defined by the integration of different agricultural practices (choosing plant material, sowing characteristics, fertilization, irrigation, pest, weeds and diseases control, crop diversification strategy, etc.) Then, the adoption of CA technology should be adjusted to those agricultural and cropping systems to assess water productivity in diverse scenarios. For these reasons, the CAMA project aimed to give new research evidence on water conservation and water efficient use, providing technical and scientific knowledge of water-saving methods, more tolerant crops/genotypes, residues mulching and soil water conservation capacity. CAMA aimed to show the improvement in water use efficiency in Mediterranean agricultural systems with legume-based crop rotations, mixed crops and conservation agriculture implementation.

2. Methodology

2.1. Field experiments network

CA was developed in many areas around the world with successful adoption by farmers, however in Mediterranean areas still there is a limited expansion. Despite the Mediterranean basin having pedo-climatic conditions and traditional agriculture that make a very suitable area for the adoption of CA, due to different reasons this adoption is still limited. Crop yield is one main reason for the adoption of whatever crop technology, but also the relation with the water use and the efficiency of this utilization is needed and regarding water is a limited resource in Med conditions. Mediterranean basin is a diversified cropping area in type of crops and cropping systems. CA could be adopted in all diverse crops (field crops, orchards and even horticultural crops). The cropping system is defined by the integration of different agricultural practices (choosing plant material, sowing characteristics, fertilization, irrigation, pest, weeds and diseases control, crop diversification strategy, etc.) Then, the adoption of CA technology should be adjusted to those agricultural and cropping systems to assess productivity in diverse scenarios.

For this reason, one of the main objectives of the CAMA project is to assess soil water conservation, water use by crop and water productivity by the indicator water use efficiency, defined this last by the ratio between the crop yield and the water used by crop. All that, comparing different soil management systems in combination with other practices in different countries of the Mediterranean basin. For that, a limited network of experiments (running for several years or newly established for the project) has been used in the frame of the project.

2.2 Water use and water use efficiency. Measurements

In these field experiments, yield and the main water balance components (rainfall, soil water content) have been measured and crop water use (WU) and water use efficiency (WUE) (for biomass and commercial yield) have been evaluated. For the calculation of water use and water use efficiency, soil water dynamics, water balances and relation with crop yield have been measured in experiments or commercial fields. The gravimetric method has been used mostly to evaluate soil water content at the beginning and the end of the crop cycle at the root depth. In some cases, other methods as modeling have been used to estimate the water balance to relate to the crop yield. Soil water dynamics should be established with soil water content measurements in several crop stages. Also, crop yield should be measured as has been described in Deliverable 5.1. Different methods have been used by the research teams in different countries. In the annexe 2, the different methodology is described. Anex

2.3 Statistical analysis

To analyze the significance of the differences between treatments especially those referring to comparison between tillage systems, different statistical analyses have been done by the research groups and can be seen in the Results section.

3. Results

3.1 CREA (Italy)

The results of the three growing seasons within the project are shown for this experimental field in Foggia Italy.

Growing season 2020-2021: Sowing of broad bean (*Vicia faba* var. *minor* L.) was done on 23 December 2020 and harvested on 25 June 2021. In the NT treatment, a soil water content lightly greater than MT was observed either at sowing or at harvest time in the 0-30 cm soil depth (Fig. 1 and 2), but not significantly different at statistical analysis.

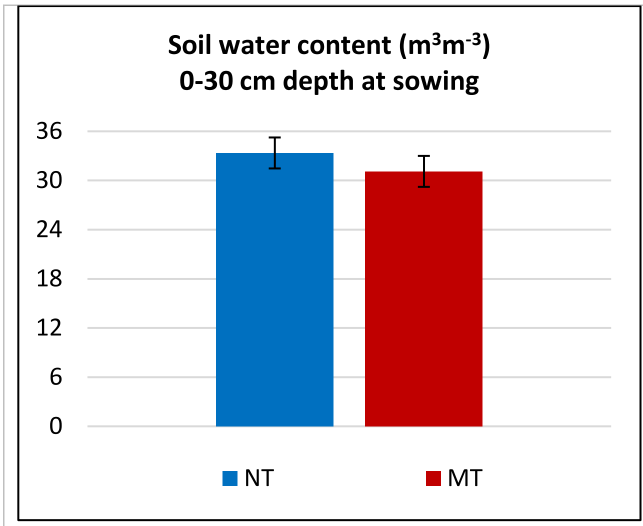

Figure. 1 Soil water content at 0-30 cm depth measured with the gravimetric method at **sowing** time (December 2020) (P>0.05, n.s.). The columns are average values and bars indicate the standard deviations.

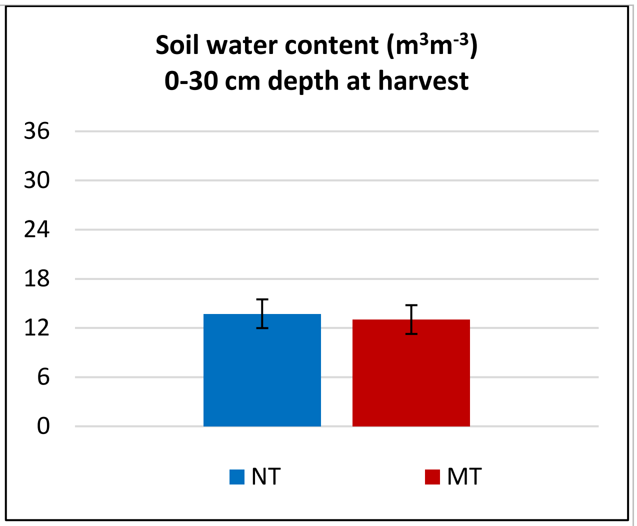

Figure. 2. Soil water content at 0-30 cm depth measured with gravimetric method at **harvest** time (June 2021) (P>0.05, n.s.). The columns are average values and bars indicate the standard deviations.

During the spring, the measurements with the WET-2 Delta T © probe in the 0-5 cm depth were variable and more favorable to MT in 2 out of 4 samplings (Fig. 3).

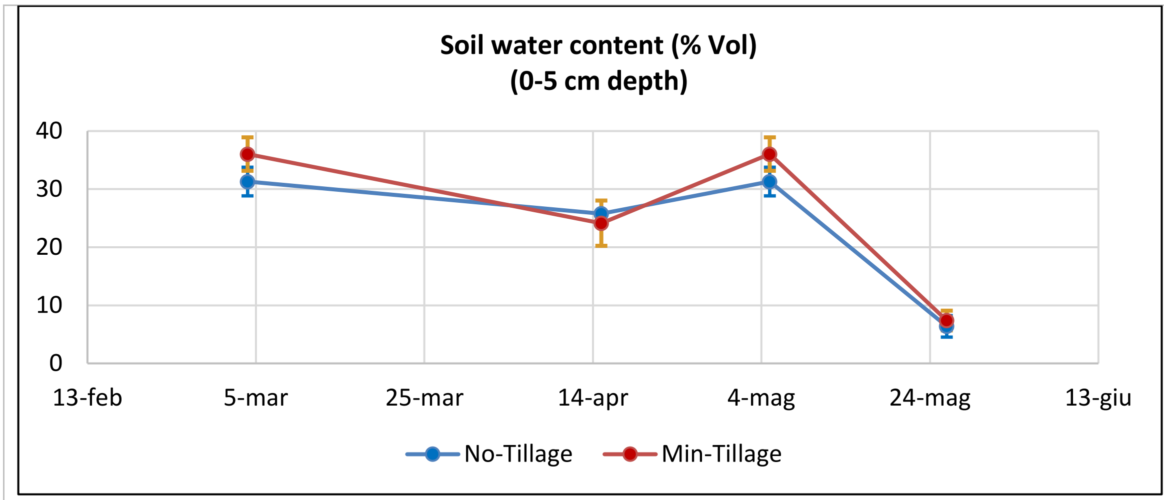

Figure. 3. Soil moisture at 0-5 cm depth measured with WET-2 Delta T © probe in the 2020-2021 season in Foggia. The bars indicate the standard deviations.

The seasonal water use of the two different treatments in this experiment showed a larger value in NT than in MT treatment (303 vs 285 mm). The severe drought in the terminal phase of the crop growth and the soil with vertical characteristics influenced the soil water content at harvest time. In fact, it went down below the soil wilting point (18.0 m^3 m^{-3}) also for the deep cracks formation (on average, 13.7 and 13.0 m^3 m^{-3} for NT and MT, respectively). The grain and biomass WUE resulted similar between the treatments, with a light superiority in MT for biomass WUE (Table 1).

Table 1. Water use and Water Use Efficiency of broad bean in Foggia (2021) (averages and standard deviations).

	Soil Water Depletion (mm) 60 cm depth	Water Use (mm)	WUE grain (kg/ha/mm)	WUE biomass (kg/ha/mm)
NT	66.59±21.78 **a**	302.59±21 **a**	3.51±0.42	12.55±1.81
MT	48.82±16.29 **b**	284.82±16 **b**	3.48±0.36	13.96±1.68

Growing season 2021-2022: Sowing of durum wheat (*Triticum durum* Desf.) was done on 21 December 2021. The soil water content in the 0-30 cm soil depth at sowing and at harvest was not significantly different between the two treatments (Fig. 4 and 5)

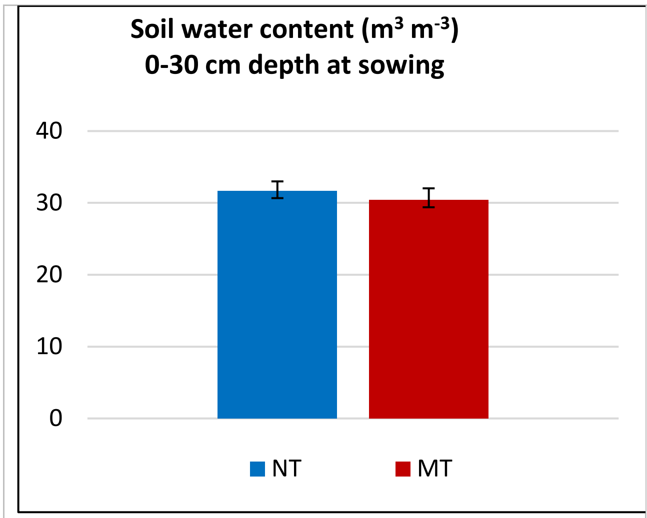	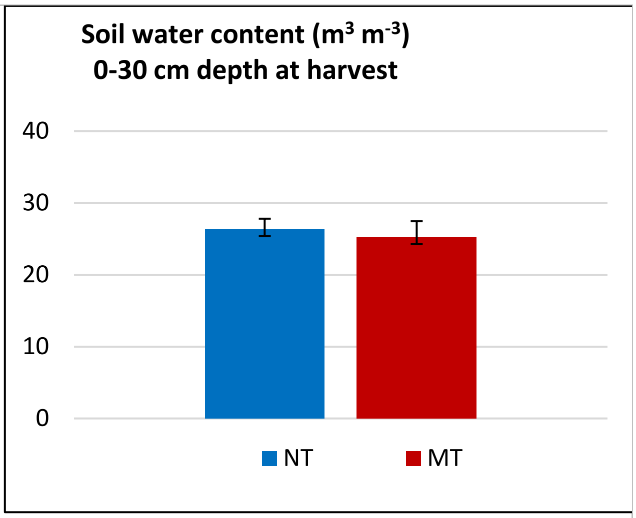
Figure. 4. Soil water content at 0-30 cm depth measured with the gravimetric method at sowing (December 2021) (P>0,05, n.s.). The columns are average values and bars indicate the standard deviations.	**Figure. 5** Soil water content at 0-30 cm depth measured with the gravimetric method at harvest (June 2022) (P>0,05, n.s.). The columns are average values and bars indicate the standard deviations.

The soil water depletion from sowing to harvest and the seasonal water use were not statistically different between the two treatments even if a slightly larger value in NT than in MT, emerged. On the contrary, WUE of grain yield resulted higher in MT than in NT treatment (20.1 vs 17.5 kg/ha/mm) (Table 2)

Table 2. Water use and Water Use Efficiency of durum wheat in Foggia (2022) (averages and standard deviations). Means with different letters are significantly different (Tukey test at P=0.05 level).

	Soil Water Depletion (mm) 60 cm depth	Water Use (mm)	WUE grain (kg/ha/mm)
NT	31.96±11.86	235.76±11.86	17.48±1.09 **b**
MT	29.14±18.89	227.11±20.53	20.12±2.48 **a**

Growing season 2022-2023: Sowing of chickpea (*Cicer arietinum* L.) was done on 14 February 2023 and harvest on 4 August 2023. Soil water content at sowing and harvest in the 0-30 cm soil depth was not significantly different between the two treatments (Fig. 6 to 8). The soil moisture in the upper layer (0-5 cm depth) measured at the sowing with Hydrago probe, resulted significantly greater in NT than in MT (28.1 vs 20.6 m^3m^{-3}, respectively for NT and MT) for the mulching effect on moisture conservation due to surface residues (Fig. 8).

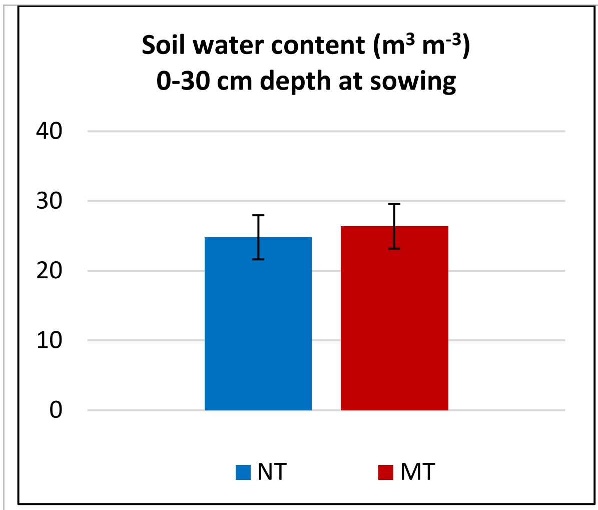

Figure. 6. Soil water content at 0-30 cm depth measured with the gravimetric method at **sowing** (February 2023) (P>0.05, n.s.). The columns are average values and bars indicate the standard deviations.

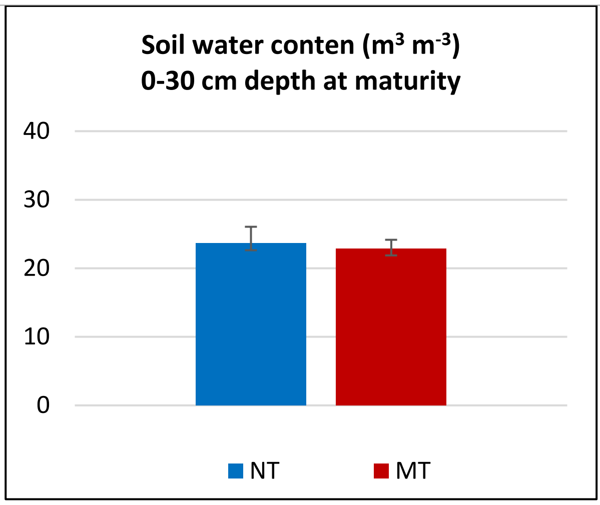

Figure. 7. Soil water content at 0-30 cm depth measured with the gravimetric method at **maturity** (June 2023) (P>0.05, n.s.). The columns are average values and bars indicate the standard deviations

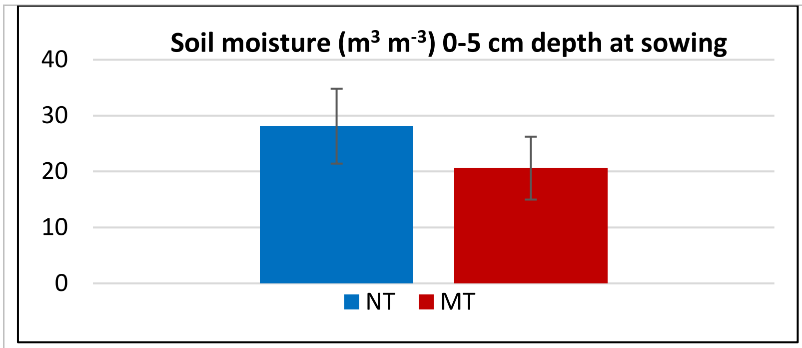

Figure. 8. Soil water content at 0-5 cm depth measured with HydraGo © probe at **sowing** (February 2023) (P<0.001).
The columns are average values and bars indicate the standard deviations.

The seasonal water use of the two different treatments showed a larger value in MT than in NT treatment (182 vs. 171 mm), mainly due to a reduced chickpea biomass in NT and consequently to a lower water uptake than in MT. The grain and biomass WUE resulted in differences between the treatments, with higher values in MT both for seed WUE and biomass WUE (Table 3)

Table 3. Water use and Water Use Efficiency of chickpea in Foggia (2023) (averages and standard deviations). Means with different letters are significantly different (Tukey test at P=0.05 level).

	Soil Water Depletion (mm) 60 cm depth	Water Use (mm)	WUE grain (kg/ha/mm)	WUE biomass (kg/ha/mm)
NT	6.98±5.84 **b**	170.78±5.92	3.30±1.27 **b**	12.22±3.61 **b**
MT	20.99±14.16 **a**	181.99±15.19	9.61±2.03 **a**	27.51±6.74 **a**

3.2. ARVALIS (France)

Pluriannual analysis

Table 4 shows in the last column the crop water productivity in kg/m3. Converted to WUE in kg/mm/ha, the productivity of the three growing seasons ranged between 9 and 14 kg/mm/ha depending on the growing season and crop.

Table 4. Water productivity (1 kg m^{-3} = 10 kg/mm/ha) on Oraison platform in 2021, 2022, and 2023 in rainfed conditions. The potential yield was estimated by the model Garric ®.

Year	Potential climatic Yield (T/ha)	Biologic Yield (T/ha)	% of potential climatic yield realized	Spike_m²	Grains_spike	Grains_m²	Dry Thousand Kernel Weight (g)	Protein_ content (%)	Flowering biomass (T/ha)	N concentration in above ground biomass at flowerinf (%)	NNI at flowering	N abs at flowering in above-ground biomass (kg/ha)	Total Nitrogen inputs (kg N/ha)	Rainfall between sowing and maurity (mm)	Water productivity (kg/m3)
2021	8.0	5.0	63%	412.8	26.3	11339.3	37.7	14.3	10.0	0.82	158.7	170.0	35.8	555.0	0.9
2022	2.9	2.8	91%	320.2	23.3	7286.8	32.6	17.5	7.1	0.81	130.2	160.0	67.7	211.7	1.4
2023	4.3	4.6	107%	411.8	25.5	10428.9	38.6	16.7	7.3	0.78	127.0	140.0	32.0	532.0	0.9

Growing season 2020-2021. Sowing of durum and bread wheat on two dates : October 20 (B4 to B16) and November 20 (B17, B18). In this growing season, water use efficiency ranged between 7 to 12 kg/mm/ha for wheat /durum and bread depending on the preceeding crop (Table 5).

Table 5: Water productivity (1 kg m^{-3} = 10 kg/mm/ha) on Oraison platform in 2020-21 in rainfed conditions. The potential yield was estimated by the model Garric ®. Tukey test at a confidence interval of 95%.

Plot	irrigation	Crop n-1	Crop	Genotypes	Biologic Yield (T/ha)	Tukey	% Potential yield realized	Spike/m²	Grain/spike	Grains/m²	Dry Thousand Kernel Weight (g)	Protein content (%)	Flowering biomass (T/ha)	NNI at flowering	N abs at flowering in above-ground biomass (kg/ha)	Nitrogen input / Yield (kgN/T)	Water productivity (kg/m3)
B14	no	Alfalfa	Bread wheat	Forcali	4.6	a	112%	434.4	23.3	10104.9	38.9	16.2	7.9	0.78	132.9	31.1	0.9
B13	no	Alfalfa	Bread wheat	Forcali	3.7	ab	89%	334.9	25.7	8296.8	37.7	17.2	8.4	0.76	133.3	39.5	0.7
B18	no	Onobrychis	Durum whea	Portuguese genetic	5.1	b	112%	461.5	28.5	13155.1	33.1	17.0	7.5	0.82	136.0	28.8	1.0
B4	no	Fababean	Durum whea	Mixture	6.5	b	142%	603.6	27.2	16563.9	33.4	16.4	8.4	0.89	156.0	22.0	1.2
B16	no	Alfalfa	Durum whea	Mixture	4.4	b	106%	388.0	23.1	8952.1	41.4	16.3	7.1	0.73	117.0	32.7	0.8
B15	no	Alfalfa	Durum whea	Mixture	4.4	b	108%	334.4	25.3	8588.9	43.9	16.6	6.2	0.74	109.3	35.0	0.8
B17	no	Onobrychis	Durum whea	Portuguese	4.0	b	90%	316.1	29.1	9054.4	37.8	16.4	7.1	0.77	122.7	35.3	0.8
B5	no	Fababean	Durum whea	Mixture	4.7	b	105%	421.9	22.4	9430.8	42.3	17.1	6.0	0.75	109.3	30.6	0.9

Growing season 2021-2022. For the season 2021-2022, 13 plots have been sowed with bread and durum wheat. On October 15 in irrigated (I1-I2; I3-I4) or in rainfed conditions (B23, B22, B25, B26). One modality was conducted without fertilization (I3-I4 0N). On January 16 in irrigated (I5, I6) or in rainfed conditions (B21, B22). Two modalities were conducted without fertilization (I5 0N, I6 0N). Table 6. Shows the results on this growing season.

Table 6. Water productivity (1 kg m^{-3} = 10 kg/mm/ha) on Oraison platform in 2021-22 in rainfed conditions. The potential yield was estimated by the model Garric ®. Tukey test at a confidence interval of 95%.

Year	Plot	irrigation	Crop n-1	Crop	Genotypes	Potential Yield (T/ha)	Biologic Yield (T/ha)	Tukey test	% Potential yield realized	Spike/m²	Grain/spike	Grains/m²	Dry Thousand Kernel Weight (g)	Protein content (%)	Flowering biomass (T/ha)	NNI at flowering	Nitrogen input / Yield (kgN/T)	Water productivity (kg/m3)
2021	B6	no	Chickpea	Durum whea	Mixture	8	6.27	a	78%	403	25.2	13922	38.3	14.0	9.8	0.89	27.4	1.13
2021	B8	no	Chickpea	Durum whea	Mixture	8	5.27	a	66%	422	28.2	11381	39.4	14.1	10.2	0.76	32.6	0.95
2021	B12	no	Chickpea	Durum whea	Mixture	8	5.26	a	66%	484	25.4	12354	36.2	14.0	12.3	0.94	33.7	0.95
2021	B10	no	Chickpea	Durum whea	Mixture	8	5.10	a	64%	426	28.3	11967	36.2	14.2	10.7	0.86	34.3	0.92
2021	B11	no	Fababean	Durum whea	Mixture	8	5.04	a	63%	403	29.1	11693	36.6	14.0	10.5	0.77	34.2	0.91
2021	B7	no	Fababean	Durum whea	Mixture	8	4.92	ab	61%	372	28.2	10579	39.5	14.2	9.6	0.75	37.2	0.89
2021	B9	no	Fababean	Durum whea	Mixture	8	3.44	b	43%	380	20.8	7783	37.6	15.3	7.5	0.78	50.0	0.62

Growing season 2022-2023.

Table 7 shows the results for the growing season.

Table 7. Water productivity (1 kg m^{-3} = 10 kg/mm/ha) on Oraison platform in 2022-23 in rainfed conditions. The potential yield was estimated by the model Garric ®. Tukey test at a confidence interval of 95%.

Year	Plot	irrigation	Crop n-1	Crop	Genotypes	Biologic Yield (T/ha)	Tukey test	% Potential yield realized	Spike/m²	Grain/spike	Grains/m²	Dry Thousand Kernel Weight (g)	Protein content (%)	NNI at flowering	Nitrogen input / Yield (kgN/T)	Water productivity (kg/m3)
2022	I1-I2	yes	Onobrychis	Bread wheat	Forcali	10.3	a	145%	847	31.1	26149	33.6	13.2	0.9	18.0	2.2
2022	I3-I4	yes	Onobrychis	Durum whea	Mixture	9.0	ab	125%	668	30.6	20592	37.3	13.9	1.0	21.3	2.0
2022	I3-I4 0N	yes	Onobrychis	Durum whea	Mixture	7.2	b	100%	496	31.9	14724	41.6	10.4	0.6	0.0	1.6
2022	I5	yes	Onobrychis	Durum whea	Portuguese genetic	4.6	c	73%	530	19.7	10443	37.3	17.6		36.6	1.5
2022	B23	no	Maize	Durum whea	Mixture	3.8	c	121%	428	19.2	8131	39.9	17.9	0.7	52.7	1.5
2022	B26	no	Maize	Bread wheat	Forcali	3.7	c	112%	425	24.6	10545	29.9	16.3	1.0	55.1	1.4
2022	I6	yes	Onobrychis	Durum whea	Portuguese genetic	3.6	cd	57%	506	17.2	8721	35.2	17.8		51.5	1.2
2022	I6 0N	yes	Onobrychis	Durum whea	Portuguese genetic	3.6	cd	57%	379	23.0	8832	34.4	16.7		0.0	1.1
2022	B24	no	Maize	Durum whea	Mixture	2.8	cd	87%	316	20.4	6544	35.7	17.5	0.8	79.3	1.1
2022	I5 0N	yes	Onobrychis	Durum whea	Portuguese genetic	2.7	cd	42%	358	18.5	6818	33.1	18.3		0.0	0.8
2022	B25	no	Maize	Bread wheat	Forcali	2.6	cd	71%	316	25.0	8040	31.7	15.8	0.8	83.6	1.0
2022	B21	no	Maize	Durum whea	Fado	1.8	d	78%	206	26.3	5289	29.0	18.3		68.3	1.6
2022	B22	no	Maize	Durum whea	Vadio	1.8	d	77%	219	24.3	5172	29.1	19.0		68.9	1.6

3.3. HAO (Greece)

Results of water use efficiency (kg/mm/ha) are presented for *L. sativus* and barley growing seasons (2020-2021, 2021-2022), whereas only Water Use (%) is presented for barely grown in 2022-2023 due to limitations in data analysis by using the AQUACROP model. Crop failure due to limited rainfall and extremely high temperatures in the summer 2020 and 2021 led to crop failures for *P. milliaceum* and *S. bicolor*. Therefore, water use efficiency has not been calculated for these two crops.

Growing season 2020-2021. Estimation of Water Use and Crop Water Use Efficiency in *Lathyrus sativus* sown for both Conventional Tillage (CT) and Minimum tillage (MT) on 1st December 2020 in Greece. It was observed small difference between the ETa values of the two treatments despite the differences in the yield. The similarity in ETa values resulted from the existence of a larger expansion of weeds in CT, which acted as a co-existent crop with *L. sativus*, affecting soil moisture conditions. Various adjustments in the simulations with AQUACROP using soil moisture showed ETa values around ~212 mm for both cases (MT and CT). The calculation was based on the same soil moisture and the same precipitation occurred in both tillage systems. The results showed that total precipitation was equal to 313.6 mm from 1/12/2020 to 23/06/2021, whereas WU (%)= ETa/P= (212)/(313.6) x 100= 67.6% for both Minimum Tillage (MT) and Conventional Tillage (CT). Crop WUE revealed a difference in favor of MT (13,2 kg/mm/ha) compared to CT (8,9 kg/mm/ha), due to greater yield under MT because of the less impact of weeds on yield (Table 8). This difference was attributed to the lower yield of *L. sativus* because of the increased weed populations observed in this system compared to MT (as described in 5.1 Delivarble).

Table 8: Water Use Efficiency (WUE) for *L. sativus* yield in MT and CT.

Tillage system	WUE (kg/mm/ha)	Grain yield (t/ha)
MT	13.2	2.79
CT	8.9	1.89

Growing season 2021-2022. Estimation of Water Use and Crop Water Use Efficiency in *Hordeum vulgare* grown under Minimum tillage (MT) and under Conventional Tillage (CT) in Greece for the period 2021-2022. Barley (greek cv. Triptolemos) was sown on 17 November 2021 both under CT and MT. The total amount of ET_o for the growing season was estimated at 568.8 mm, while the total rainfall was 369.2 mm. The results revealed 183.5 and 193 for the ET_{aCT} and the ET_{aMT}, respectively, which led to 52.3% and 49.7% WU, 2.25 kg/mm/ha and 2.21 kg/mm/ha for barley grown under MT and CT, respectively (based on 4.35 t/ha and 4.05 t/ha grain yield for MT and CT, respectively) **(Table 9).**

Table 9: Water Use Efficiency (WUE) and Crop Water Use Efficiency (CWUE) for barley yield in MT and CT in 2021-22

Tillage system	WUE (kg/mm/ha)	Grain yield (t/ha)
MT	22.5	4.35
CT	22.1	4.05

Growing season 2022-23. Barley (cv. *Nure*) was sown on 30 November 2022 both under CT and MT. That year the field was highly infested by weeds and there was a delayed weed control that led to lower grain yields compared to the yields of the previous year, although precipitation was adequate particularly the period from March to May 2023. The total rainfall for the growing period was was 372.4 mm and the total amount for the ET_0 was 545.2 mm.

As mentioned above, for the experimental period of 2022-2023, the rainfall during the seed formation and filling was extremely higher than usual making the conditions in the field similar to an irrigated crop. For this reason the AQUACROP model provided extremely high yields (6.5 tn/ha), which did not correspond to the observed MT and CT yields, that were significantly lower mainly due to weed infestation and the late weed control in both MT and CT fields. It should be mentioned that although weed infestation was greater in CT in terms of weed density, the crop managed to compete the weeds better than in MT (as described in 5.1 Deliverable). That was due to other causes occurred in MT that period that resulted in lower barley growth and development compared to those grown in CT (5.1 Deliverable). For these reasons, the modelling procedure was neglected because it was impossible to consider the aforementioned elements. In order to provide an estimation of water use (WU), we used the estimated crop water use efficiency (CWUE) of the previous experimental year 2021-2022 where CWUE of CT was 22.1kg/mm/ha while of MT was 22.5 kg/mm/ha (Table 9), which were almost similar. Assuming that for both MT and CT the CWUE for 2022-2023 was similar and on average ~22.5 kg/mm/ha, we estimated the real evapotranspiration for MT and CT based on the observed yields as follows:

ETa_CT= (Yield_CT)/(CWUE_CT)=(390 kgr/str*)/(2.25 kgr/m^3) = 173.3 mm (since 1 mm = 1 m^3/str)

ETa_MT= (Yield_MT)/(CWUE_MT)=(302 kgr/str)/(2.25 kgr/m^3) = 134.2 mm (since 1 mm = 1 m^3/str)

*1 str=1/10 of hectare

Considering the above only the (%) WU was calculated according to the following:

WU = (Water beneficially used)/(Water delivered) ×100 = (real evapotranspiration)/(rainfall) ×100 = ETa/P×100

%WU CT = (173.3/372.4)×100 = 46.5%

%WU_MT = (134.2/372.4)×100 = 36.1%

The results showed higher WU for the plants grown under MT and CT (Table 10).

Table 10: Water Use (WU) and barley yield in MT and CT in 2022-23

Tillage system	WU (%)	Grain yield (t/ha)
MT	46.5	3.02
CT	36.1	3.90

3.4 UdL-CSIC (Spain)

The results of the three growing seasons within the project are shown for this experimental field in Senés de Alcubierre (Spain). Table 11 shows the results of water use by cropping in the three growing seasons studied in the CAMA project in the rotation Wheat - Pea Crop - Barley. Differences in water used by crops wer observed between the years are consistent with the climate recorded in the three growing seasons. The 2022-23 season was the driest growing season registered in the last 40 years (less than 250 mm) and Wuse by crop was lower. The water use ranged between less than 300 mm to more than 350. Differences in WU were affected by the tillage system only in the first year and in the wheat crop. Fertilization dose was affected positively also in the first year but with less consistency in the second and third. No differences in WU were observed due to the fertilizer type (combination of dose and product).

Table 11. Water use by crop (mm) in wheat, pea crop and barley under different tillage, fertilization N dose and type of fertilizer products from 2020 to 2023 growing seasons in Senes de Alcubierre (Huesca, Spain). The data were subjected to analysis of variance according to the randomized block design. The means separation test was the Student-Newman-Keuls at a 0.5 probability level. GLM procedure of the JMP program was used in the analysis of variance and mean separation test. Mean values labelled with the same letter were not significantly different at $p < 0.05$ in the ANOVA and t-student tests.

Growing season	2020-21		2021-22		2022-23	
Crop	Wheat Crop		Pea crop		Barley crop	
Tillage system						
CT	353,00	b	309,00	a	302,00	a
NT	365,00	a	309,00	a	297,00	a
N fertilization dose						
0	*346,00*	b	*306,00*	*a*	*299,00*	ab
75	*358,00*	*a*	*304,00*	*a*	*288,00*	b
150	*366,00*	*a*	*315,00*	*a*	*311,00*	a
Treatment combination						
0	346,00	b	306,00	a	299,00	a
Medium N (75) -Mineral	354,00	ab	299,00	b	273,00	a
Medium N (75) -Organic	362,00	a	310,00	a	302,00	a
High N -MIN (150)- Mineral	361,00	a	319,00	a	312,00	a
High N -ORG (150)-Organic	371,00	a	312,00	a	311,00	a

Table 12 shows the results of water use efficiency (WUE) in the three growing seasons studied. In this case, WUE ranged from nearly 14 kg/mm/ha in some cases of the second season and for pea crops and less than 1 kg/mm/ha en the case of the third growing season in the case of the barley crop.
More than the effect of the crop, year had the main effect. In all the cases WUE was determined by the yield more than the WU by crop. The main patterns of the WUE are coincident with the crop yield (Deliverable 5.1). Differences in tillage system were obtained in the growing seasons and in all crops, but only significant in the second and third. NT showed higher WUE than CT. The effect of N fertilization dose was positive in 2 of the 3-growing seasons and no differences in N dose in the last 2022-23. No interaction was observed between the Tillage system and N fertilization dose. In all cases, higher WUE were obtained in NT. Combinations of treatment dose and type and fertilizer product (mineral vs. organic) showed a positive response in WUE to organic fertilizer more than in mineral fertilizer but only significant in two of the three years and not always significant.

Table 12. Water use efficiency (kg/mm/ha) in wheat, pea crop and barley under different tillage, fertilization N dose and type of fertilizer products from 2020 to 2023 growing seasons in Senes de Alcubierre (Huesca, Spain). The data were subjected to analysis of variance according to the randomized block design. The means separation test was the Student-Newman-Keuls at 0.5 probability level. GLM procedure of the JMP program was used in the analysis of variance and mean separation test. Mean values labelled with the same letter were not significantly different at $p < 0.05$ in the ANOVA and t-student test.

Growing season	2020-21		2021-22		2022-23	
Crop	Wheat Crop		Pea crop		Barley crop	
Tillage system						
CT	5,19	a	6,36	b	0,97	b
NT	7,37	a	13,29	a	2,15	a
N fertilization dose						
0	*5,24*	*b*	*4,53*	*b*	*1,52*	*a*
75	*6,90*	*a*	*10,17*	*a*	*1,60*	*a*
150	*6,18*	*ab*	*12,13*	*a*	*1,59*	*a*
Treatment combination						
0	5,24	b	4,52	c	1,52	a
Medium N (75) -Mineral	5,65	b	8,74	b	1,52	a
Medium N (75) -Organic	8,15	a	11,60	a	1,68	a
High N -MIN (150)- Mineral	5,62	b	9,50	ab	1,31	a
High N -ORG (150)-Organic	6,75	ab	14,76	a	1,81	a

3.5. INRA (Morocco)

The CAMA project included field trials in Morocco spanning three consecutive cropping seasons (2020-21, 2021-22, and 2022-23). Evaluation of Durum wheat yield and water use efficiency (WUE) took place during the 2020-21 and 2021-22 cropping seasons. Due to a severe drought in the third cropping season in 2022-23, the crops failed in Central Morocco in this last season specifically at the Merchouch site. During the two cropping seasons (2020-21 and 2021-22), the total rainfall recorded at the Merchouch experimental station was 347 mm and 251 mm, respectively. However, in the 2022-23 season, the rainfall recorded was less than 171 mm.

Growing season 2020-2021

In this cropping season, 5 durum wheat germplasm were tested under 2 tillage types (NT vs. CT) and 3 doses of N fertilization (35N, 55N and 75N). Table 13 shows the grin yield of the experiment. The analysis of variance (table 14) highlighted the effect of tillage systems on grain yield indicators.

Table 13. Durum Wheat grain yield (t ha^{-1}), measured at the end of the experiment during the cropping season 2020-2021, for tillage types, nitrogen doses (kg N ha^{-1}), and varieties. Means (n=3), with (standard deviations), followed by the same letter are not statistically different at the 0.05 significance level using the Duncan post-hoc test. NT= No tillage, CT= Conventional tillage.

Nitrogen (kg N ha^{-1})	Tillage / Variety	Faraj	I.C	Louiza	M.G	Nachit	Mean	Mean
35	NT	4.31 (0.34)	4.74 (0.42)	3.42 (0.49)	4.52 (0.96)	4.47 (0.83)	4.29 (0.73)	4.09 (0.75) A
	CT	4.46 (0.34)	3.87 (0.70)	3.21 (0.55)	3.40 (0.41)	4.52 (0.74)	3.89 (0.73)	
55	NT	4.32 (0.17)	3.88 (0.66)	2.93 (0.66)	3.97 (0.48)	5.14 (1.03)	4.05 (0.93)	3.92 (0.81) A
	CT	3.77 (0.35)	4.24 (0.19)	3.34 (0.55)	3.05 (0.13)	4.48 (0.76)	3.78 (0.67)	
75	NT	4.04 (0.59)	3.93 (0.44)	3.17 (0.47)	3.95 (0.13)	4.24 (0.03)	3.86 (0.51)	3.72 (0.56) A
	CT	3.86 (0.20)	3.63 (0.89)	3.01 (0.15)	3.43 (0.73)	3.90 (0.50)	3.57 (0.59)	
Mean	NT	4.22 (0.38)	4.18 (0.61)	3.17 (0.52)	4.15 (0.61)	4.62 (0.78)	4.07 (0.75)	
	CT	4.03 (0.42)	3.91 (0.63)	3.19 (0.42)	3.29 (0.46)	4.30 (0.66)	3.75 (0.67)	
Mean		4.13 (0.40) a	4.05 (0.62) b	3.18 (0.46) c	3.72 (0.68) b	4.46 (0.72) a	3.91 (0.72)	

Table 14, shows the effect of each parameter (Tillage type, Nitrogen and Variety). Also, the trial pointed out the effect of the tillage system* genotype* Variety interaction. The analysis showed that the only germplasm effect was significant on the grain yield (Table below). As WUE is directly linked to Grain yield (WUE= GY/annual water balance), we conclude that under these low rainfall conditions, germplasm was significantly impacting the grain yield. Which highlighted the need to select the suitable germplasm to improve the WUE.

Table 14. ANOVA results for wheat grain and straw yield (t ha^{-1}), measured at the end of the experiment during the cropping season 2020-2021. ns: not significant; *, **, and ***: significant at the 0.05, 0.01, and 0.001 levels, respectively.

Wheat yield	Grain		Straw	
Source of variation	**F value**	**p-value**	**F value**	**p-value**
Tillage (T)	4.40	0.171 ns	1.20	0.388 ns
Nitrogen (N)	3.95	0.064 ns	2.06	0.190 ns
Variety (V)	14.62	<0.001 ***	6.41	<0.001 ***
T*N	0.14	0.876 ns	0.13	0.880 ns
T*V	1.60	0.189 ns	2.12	0.093 ns
N*V	0.76	0.637 ns	0.16	0.996 ns
T*N*V	1.07	0.398 ns	0.70	0.690 ns

The Duncan post-hoc test showed that the **Louiza variety had the lowest WUE (8.9 kg/ha/mm), followed by I.C and M.G with intermediate WUE (11.3 and 10.4 kg/ha/mm), and finally Faraj and Nachit with the highest grain yield (11.5 and 12.5 kg/ha/mm) (Table above).** A slightly higher grain yield was attained under NT (4.07 t ha-1) compared to CT (3.75 t ha-1). The tillage type effect on yield was not significant even though there were significant differences between soil properties (especially Organic Carbone) corresponding to the two tillage types. This may be explained, as above, by the water stress that impacted the crop yield. For nitrogen doses, mean grain yields were 4.09, 3.92, and 3.72 t ha-1 under 35, 55, and 75 kg N ha-1, respectively. The water stress is likely behind the absence of nitrogen dose effect on crop yield.

Growing season 2021-2022

In this cropping season and due to drier conditions (rainfall less than 257 mm), it was difficult to affect the nitrogen fertilization. 4 durum wheat germplasm were tested under 2 tillage types (NT vs CT). The tables below (tables 15 and 16) show the analysis of variance that highlighted the effect of the tillage system on wheat yield.

Table 15. Effect of tillage system (T), genotype (G) and their interaction (T*G) on grain yields (GY) and straw yields (SY) of durum wheat at the Merchouch experimental field in 2021-2022. DL: degree of freedom; MS: mean square; P significance level: * (<0.05), ** (<0.01), ***(<0.001), ns: not significant

Factor	DF	GY		SY	
		MS	**P**	**MS**	**P**
T	**1**	**43,422**	*****	**60,173**	****
G	**3**	**11,152**	****	**30,764**	****
T x G	**3**	**11,074**	****	**22,829**	***
Residual	**16**	**1,727**		**5,558**	
Total	**23**	**5,989**		**13,473**	

Regarding the WUE, although there was a clear improvement in no-till compared to conventional tillage in all genotypes, it recorded an important increase in the Faraj variety (3.15 kg/ha/mm in no-till compared to 0.6 kg/ha/mm in conventional seeding). Finally, regardless of the genotype, no-till WUE was around 1.63 kg/ha/mm which is 3 times more than in conventional sowing (see Table 16). This could be explained by dry soil conditions observed under CT (more cracks) vs in the NT, especially in tillering period. This confirms that NT system is more resilient than CT in cereal based system.

Table 16. Water Use efficiency of durum wheat genotypes in conventional and no-till in Merchouch in 2021-2022

WUE	Genotype	No tillage		Conventionel Tillage	
WUE (kg/ha/mm)	**Faraj**	**3.15**	**aA**	**0.60**	**aB**
	M.G	**0.92**	**bA**	**0.71**	**aA**
	I.C	**0.80**	**bA**	**0.48**	**aA**
	Luiza	**1.63**	**bA**	**0.44**	**aB**
	Mean	**1.63**	**A**	**0.56**	**B**

3.6. INRAT (Tunisia)

Field trials in Tunisia conducted as part of the CAMA project were carried out over three consecutive cropping seasons, from 2020-21 to 2022-23. Evaluation of Durum wheat Water Use Efficiency (WUE) was performed for the 2020-21 and 2021-22 cropping seasons. Unfortunately, the third cropping season in 2022-23 faced failure due to severe drought conditions across Tunisia, including the Kef region. Total rainfall recorded at the El Kef experimental station was 292 mm and 246 mm for the 2020-21 and 2021-22 cropping seasons, respectively, while only 156 mm was recorded for the 2022-23 season. Table 17 summarizes the effects of Rotation (R) and Tillage (T) factors, and their interactions, on durum wheat WUE for the 2020-21 and 2021-22 cropping seasons. In the 2020-21 season, no significant effects were observed for both experimental factors and their interaction on durum wheat WUE. Meanwhile, the averaged WUE indicated that No-till (NT) and the Triennial rotation (T) had the highest rankings (Table 2). For the 2021-22 season, durum wheat WUE was significantly influenced by rotation ($P \leq 0.01$), tillage ($P \leq 0.05$), and their interaction ($P \leq 0.05$) (Table 1). Within both the biennial (B) and triennial (T) rotations, WUE in NT was significantly higher than in Conventional Tillage (CT), showing an increase of 78% and 18%, respectively (Table 18). These results suggest that the potential of no-tillage practice to enhance durum wheat WUE is dependent on the adopted crop sequences (rotation).

Especially notable for the 2021-22 season, the spring period was characterized by lower precipitation levels (about 43 mm) and a high number of day-free rainfall (78 days). Accordingly, the results suggest that NT management could contribute to greater soil moisture conservation, enabling the crop to access more water during dry periods and thereby increasing WUE compared to conventional tillage systems. These findings underscore the potential of combining practices with strategic crop rotation for optimizing durum wheat WUE, particularly in diverse and challenging climatic conditions.

In conclusion, strategic choices in rotation and tillage appear to be pivotal in adapting to and mitigating the impact of variable climatic conditions.

Table 17. Analysis of variance (F values) for the effect of the Rotation (R), Tillage (T) and their interactions on Water Use Efficiency (WUE) for the 2020-21 and 2021-22 cropping seasons. ”°” represents statistical significance at $P \leq 0.05$, ”*” represents statistical significance at $P \leq 0.05$ and “**” represents statistical significance at $P \leq 0.01$.

Source of variance	2020-21	2021-22
Rotation (R)	10.889	**13.657****
Tillage (T)	0.611	**5.405***
R*T	4.069	**2.969***

Table 18. Effect of the interactions between rotation and tillage on Water Use Efficiency (WUE), for the 2020-21 and 2021-22 cropping seasons. Column numbers displaying '±' represent the standard deviations, and

column letters indicate the Tukey HSD ($P \leq 0.05$) statistical output. Different letters within a column indicate significant differences within treatments. Rotations are Monoculture (M), Biennial (B) and Triennial (T). Tillage practices are No-till (NT), Minimum Tillage (MT) and Conventional Tillage (CT).

		2020-21			2021-22		
Rotation	**Tillage**	**WUE (kg ha^{-1} m^{-3})**			**WUE (kg ha^{-1} m^{-3})**		
M	NT	0.73	±0.19	a	0.5	±0.05	bc
	MT	0.47	±0.23	a	0.45	±0.14	c
	CT	0.45	±0.2	a	0.57	±0.21	bc
B	NT	0.71	±0.09	a	0.95	±0.09	a
	MT	0.7	±0.04	a	0.84	±0.11	ab
	CT	0.77	±0.11	a	0.53	±0.06	bc
T	NT	0.68	±0.22	a	1.08	±0.1	a
	MT	0.83	±0.18	a	0.89	±0.1	ab
	CT	0.75	±0.06	a	0.91	±0.16	ab

3.7. ENSA (Algeria)

Tables 19 and 20 show the measurement of WU and WUE by grain yield (WUEGY) in the site of MEZLOUGH (Semi-arid) under both monoculture and intercropping systems. All crop-Syst × N-level combinations affected significantly WU over most years of the experiment, except in the 2021 growing season where WU was only affected by N-level treatment. In general, the highest WU was observed in the 2021 growing season in which water consumption by the three cropping systems was increased by more than an average of 1000 m^3 ha^{-1} as compared to the 2022, 2020 and 2019 growing seasons. For chickpea monoculture, WU was globally greater under either low or moderate N-application in 2022 (174 m3 ha^{-1}) and 2019 (33 m3 ha^{-1}), as compared to their respective in high N-application (N-100). Conversely, the highest values of WU were observed in high N-application during the 2021 and 2020 cropping seasons with an increase of 150 and 62 m3 ha^{-1} in water consumption as compared to low N-application (table 1). For both sole-cropped durum wheat and mixed crop, WU was generally increased under low N-application as compared to high N-application, in particular during the 2022, 2020 and 2019 cropping seasons. Thus, a greater increase was observed during the 2022 growing season, in which WU was significantly increased by 325 and 231 m3 ha^{-1}, respectively in the durum wheat monoculture and intercropping system. In the 2021 growing season, WU was gradually increased by N-application in intercropping, where it was increased by 20 and 110 m3 ha^{-1} when upgrading respectively from N-30 to N-60 and from N-60 to N-100 dose. In the case of WUE by grain yield, data show that crop syst had a significant effect on WUEGY overall cropping years. However, it was affected significantly ($p \leq 0.05$) by both N-level and crop-syst × N-level interaction only during the 2022 and 2020 growing seasons. As compared to chickpea monoculture and intercropping, sole-cropped durum wheat was the most efficient crop in terms of water use among the three applied N-fertilizer doses, while the highest WUEGY was noted under both moderate and high N-application. Surprisingly, the greatest WUEGY was observed for sole-cropped chickpeas as compared to other cropping systems, particularly in the 2021 cropping season (table 4). When considering the mixed crop, WUEGY gradually increased from N-30 to N-60 (by 0.16 and 0.02 kg m^{-3}, respectively in the 2022 and 2020 growing seasons) and from N-60 to N-100 (by 0.21 and 0.42 kg m^{-3}, respectively in 2022 and 2020 growing season).

Table 19. Water use (WU) by chickpea durum wheat and crop mixture under different crop-N level treatments from 2019 to 2022 growing seasons in the site of MEZLOUGH. Data are means ± standard error of 4 replicates. Mean values labelled with the same letter were not significantly different at $p < 0.05$.

		WU (m^3 ha^{-1})			
Cropping system	**N-level**	**2022**	**2021**	**2020**	**2019**
Chickpea	N-30	3197.04[a]	4190.34[a]	2981.84[b]	3307.30[b]
Chickpea	N-60	3106.66[ab]	4199.88[a]	3007.83[b]	3325.92[ab]
Chickpea	N-100	3023.24[b]	4340.05[a]	3043.97[ab]	3292.01[b]
Wheat	N-30	3231.84[a]	4232.43[a]	3076.84[ab]	3364.21[a]
Wheat	N-60	3125.38[ab]	4185.35[a]	3123.34[a]	3312.01[ab]
Wheat	N-100	2906.51[c]	4325.37[a]	3089.14[ab]	3217.23[c]
Mixed crop	N-30	3244.64[a]	4191.54[a]	3095.65[ab]	3355.61[a]
Mixed crop	N-60	3048.16[b]	4211.84[a]	2997.36[b]	3381.01[a]
Mixed crop	N-100	3013.01[b]	4321.84[a]	3083.33[ab]	3479.09[a]
p-value	Cropping	0.67	0.97	≤0.01	0.01
	N-level	≤0.001	≤0.01	0.19	0.90
	Crop*N-level	0.03	0,79	0,02	0,03

Table 20. Water Use Efficiency for grain yield (WUE_{GY}) by chickpea durum wheat and crop mixture under different crop-N level treatments from 2019 to 2022 growing seasons in the site of MEZLOUGH. Data are means ± standard error of 4 replicates. Mean values labelled with the same letter were not significantly different at $p < 0.05$.

		WUE_{GY} (kg m^{-3})			
Cropping system	**N-level**	**2022**	**2021**	**2020**	**2019**
Chickpea	N-30	0.04[c]	0.43[a]	0.24[d]	0.12[c]
Chickpea	N-60	0.05[c]	0.39[ab]	0.42[c]	0.30[b]
Chickpea	N-100	0.06[c]	0.36[ab]	0.11[d]	0.43[b]
Wheat	N-30	0.84[b]	0.21[bc]	0.99[b]	1.02[a]
Wheat	N-60	1.49[a]	0.25[bc]	1.48[a]	1.04[a]
Wheat	N-100	1.41[a]	0.31[b]	1.63[a]	1.30[a]
Mixed crop	N-30	0.32[bc]	0.16[c]	0.35[d]	0.26[b]
Mixed crop	N-60	0.48[bc]	0.17[c]	0.37[d]	0.42[b]
Mixed crop	N-100	0.69[b]	0.11[d]	0.79[bc]	0.33[b]
p-value	Cropping	≤0.001	≤0.001	≤0.001	≤0.001
	N-level	0.01	0.98	≤0.001	0.49
	Crop*N-level	0,05	0,28	≤0.001	0,95

Relationship between nitrogen and water use efficiency: Simultaneous optimization of WUE and NUE by intercropping legumes-cereals under semiarid-conditions. Since interaction is possible between WUE and NUE, the values of NUEGY were plotted as a function of the WUEGY in each cropping system. The relationship in Figure 9 indicates that only both durum wheat monoculture and intercropping had a significant correlation between WUEGY and NUEGY, regardless of the three studied cropping systems. Contrastingly, the WUEGY by mixed chickpea-durum wheat was not correlated ($r^2 = 0.11$, $p \leq 0.05$) with the NUEGY of the sole cropped chickpea. Nevertheless, the strong relationship between WUE and NUE was observed in intercropping (r2 = 0.73, $p \leq 0.001$) and was greater than that found in the durum wheat monoculture system ($r^2 = 0.33$, $p \leq 0.05$). In durum wheat monoculture, each increase of 0.45 kg m^{-3} in WUEGY leads to an increase NUEGY by 1 kg kg^{-1}. In the case of intercropping, 0.62 kg m^{-3} of WUEGY promotes an increase of 1 kg kg^{-1} in NUEGY by mixed chickpea-durum wheat.

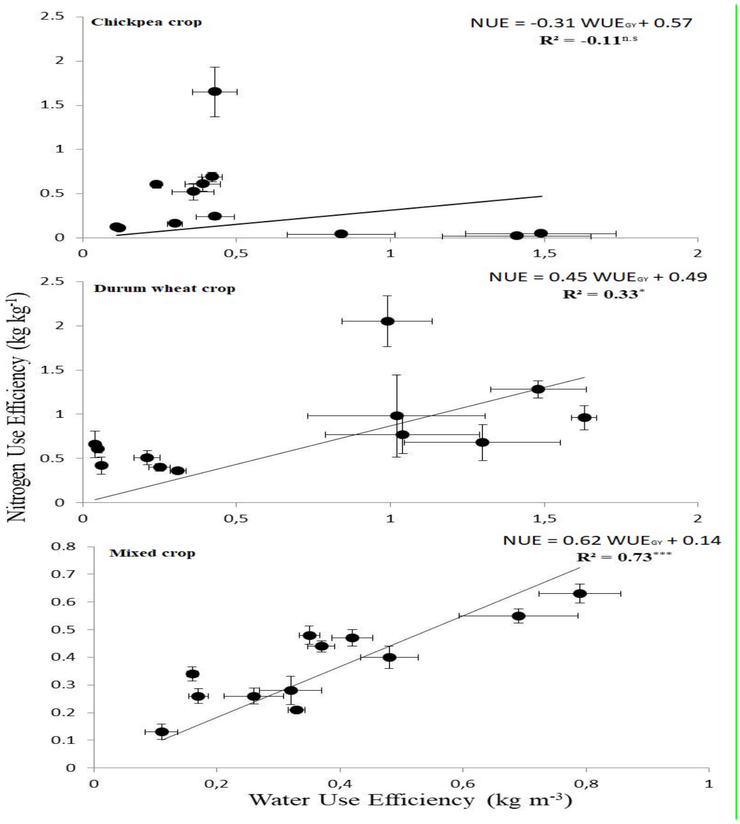

Figure 9. Water use efficiency (WUE) versus nitrogen use efficiency (NUE) for chickpea and durum wheat in both monoculture and mixture cropping systems. Linear correlation was established between all WEU and NUE values measured during the four cropping seasons and under each N-level treatment. Within 4 replicates for each N-level*year traitment. Asterisk "*" and "***" denote significant difference at $p < 0.05$ and $p < 0.001$, respectively.

The results also showed that both NUE and WUE were globally higher for durum wheat monoculture and intercropping system, except during the drought growth period that was reported in the 2021 growing season where they were greater for the chickpea monoculture. Increasing N-application from low to high dose was associated with progressive and simultaneous increase of both WUE and NUE. However, this was only confirmed in intercropping and under optimal rainfall conditions. This was probably due to much water availability during the growth period, which permitted an efficient optimization of the excessive N-fertilizer by intercropped chickpea and durum wheat during growth and yield development.

4. General Conclusions

In Italy experiments, the soil water content, in the 0-30 cm soil depth, was about the same in NT and MT, for broad bean and durum wheat. A greater significant water use value in NT was observed for broad bean, while a greater WUE value for seed production for durum wheat in MT. For chickpea crop, at sowing time, the soil moisture in the 0-30 cm soil depth was greater in MT, while in the 0-5 cm was greater in NT. At harvest time, the soil moisture measured in the 0-30 cm soil depth was not different between MT and NT.

In Greece experiments Crop Water Use Efficiency was similar for *Lathurys sativus* and for *Hordeum vulgare* grown under MT and CT during 2020-2021 and 2021-2022, respectively. In the period 2022-2023 where *Hordeum vulgare* was grown under MT and CT, water use (%) revealed higher values under conventional tillage along with higher yield compared to minimum tillage. The results suggest that increased attention should be paid to the choice of crops in the rotation when minimum tillage is applied.

In Spain experiments, the results suggest after these three growing seasons, that reduction of till and No-tillage are adequate strategies for this Mediterranean area to maintain and increase the water use efficiency. N fertilization could be adapted to the growing season and a higher dose of N fertilization did not increment this indicator. The best results are obtained under NT. In this study, the use of organic fertilizer obtained better yields making this option to reduce the use of synthetic fertilizers based on a more efficient use of the available water.

The study carried out in Tunisia in the period encompassed three consecutive cropping seasons, with the 2022-23 season marked by severe drought conditions. Analysis of durum wheat Water Use Efficiency (WUE) revealed varying impacts of Rotation (R) and Tillage (T) practices. While no significant effects were observed in the 2020-21 season, notable improvements were noted in the 2021-22 season, particularly under No-till (NT) management within biennial and triennial rotations. This highlights the importance of strategic rotation management to maximise conservation tillage benefits. In seasons with lower precipitation levels and prolonged dry periods, such as 2021-22, NT management enhanced water availability during critical growth stages, thereby increasing WUE compared to conventional tillage. The results underscore the potential of integrating NT practices with strategic crop rotation to optimize durum wheat WUE, especially in diverse and challenging climatic conditions. This highlights the importance of adaptive agricultural practices in mitigating climate variability's adverse impacts on crop productivity.

The principal findings in Algeria under the conditions of the case study (Setif región) make it possible to define relationships between WUE and NUE over a wide range of rain-fed and N-application conditions in semiarid regions (Figure 1). The obtained results highlighted the positive interaction between water and N use by mixed chickpea-durum wheat. We defined also in this work study the linear equations that describe the relationship between WUE and NUE in both durum wheat and chickpea-durum wheat intercropping systems. These findings could be considered as the first simultaneous assessment of WUE and NUE by intercropped cereals and legumes. The effective use of the major results from this field research may offer the opportunity to design and co-evaluate efficient and resilient intercropping systems in terms of N and water use in semiarid Mediterranean regions.

Annex 1. Main characteristics of the field experimental network.

CREA EXPERIMENT: Experimental design

PARTNER Country	Tasks involved in CAMA project	Location experiments	Year beginning exp./Crop rotation / Water regime	Main Treatments - Replications	Main Variables	MODELLING Model used
CREA Italy	5.1; 5.2; 5.3; 5.4	Foggia	2013 DurumWheat-Legumes Rainfed	No-Till vs. Minimum Tillage 5 replications	Grain yield Crop/plant biomass LAI Soil water content Soil compaction Hydraulic conductivity	AQUACROP BEST-K2
			2002 Monoculture of durum wheat and wheat-legumes from 2021 onwards Rainfed	No-Till vs. Minimum Tillage 3 replications	Grain yield Crop/plant biomass LAI Soil water content Soil compaction Hydraulic conductivity	AQUACROP BEST-K2

Field experiments: Foggia (Italy)

Location	Field experiment 1 was established in 2013 in Foggia (South of Italy, 41◦ 27.741’ N; 15◦ 30.389’ E) in a rainfed area. Field experiment 2 was established in 2002 in Foggia (South of Italy, 41◦ 27.050’ N; 15◦ 30.104’ E) in a rainfed area. The two experiments are 1400 m for each other.
General Climate	Temperate Continental Mediterranean Climate.
General Soil description	Soil and climatic characteristics of the site are: General and soil (0–30 cm) characteristics of the field site. Soil properties were measured at the beginning of the experiment (October 2010). Elevation (masl) 80; Annual precipitation (mm) 550; Mean annual air temperature (◦C) 13.4; Annual PET (mm) 1197 Soil classification. Vertisol Typic Haploxerert, According to the USDA classification (Soil Survey Staff, 2014). pH (H2O, 1:2.5) 8.1, EC1.5 (dS m−1) 0.21, Organic C (g kg−1) 19.0, Organic N (g kg−1) 1.23 Particle size distribution (%): Sand (2000–50 m) 19; Silt (50–2 m) 41; Clay (<2 m) 40
General description of experimental design, factor and levels of the factor.	**Experiment 1 started in 2013:** *The experimental design* consisted of the combination of two tillage practices (MT, minimum tillage; NT, no-tillage) in a randomized block design with five replications. *The cropping system:* The cropping system during the experiment consisted of broad bean (2013) followed by 5 years of continuous durum wheat, one year of fallow (2019), durum wheat (2020), and broad bean (2021). The elementary plot size was 120 m × 80 m; 30 subplots of 30 m2 each. *Tillage systems:* The MT treatment consisted of 2-3 passes of field disk cultivator (15 cm depth). A nonselective herbicide (1.5 L 36% glyphosate per hectare) was applied before sowing in the NT treatment. *Sowing:* Sowing was carried out with a no-till seeder (Gaspardo Directa 300) equipped with disk-type furrow openers set to 2–4 cm depth. *Fertilization:* It was applied at the beginning of durum wheat tillering with Entec 25-15 (400 kg ha-1). *Harvesting:* Harvesting of each elementary plot was carried out with a commercial medium-sized combine that chopped and spread over the soil surface the crop residues. *Crop residue management:* Crop residues were removed in MT chopped and left on the soil surface in NT treatment. *Other operations, variables and observations:* Daily air temperature and rainfall data were recorded with the use of an automated weather station located on the site. **Experiment 2 started in 2002:** *The experimental design* was a completely randomized block design with three replicates and elementary plots of 500 m^2. *The cropping system*: The cropping system during the experiment consisted of continuous durum wheat. From the season 2020-2021, an alternation with leguminous species has been implemented. *Tillage systems:* A two-layer tillage (deep subsoiling cultivator with rotary tiller) was carried out in MT plots. For the NT

	plot, chemical weed control as well as fertilization and sowing, were made in November (first week). *Sowing:* The sowing of durum wheat (both on MT and NT) was carried out with a seeder for direct sowing (Lasemina sodo), equipped with appropriately shaped blades for direct sowing. The chickpea was sown with a “Gaspardo No-Till 1040” seeder. *Crop residue management:* Straw was chopped into 10-15 cm in length and spread back on the plot in September (first week); this results in about 40-50 q/ha of organic matter returned to the soil. *Fertilization:* For both soil management (MT and NT), it was applied i) diammonium phosphate (18-46) 2 q ha-1 at the beginning of durum wheat tillering (basal dressing), and ii) ammonium nitrate at a rate of (34,2%) 200 kg ha-1 (top dressing). *Harvesting:* it will be carried out with the “Classic Plus Plot combine – Wintersteiger”, equipped with a continuous weighing system. *Other operations, variables and observations:* The chemical weeding was carried out on the wheat for weed control, while on the chickpea it was carried out the pre-emergency weeding. Daily air temperature and rainfall data were recorded with the use of an automated weather station located at the site.

ARVALIS EXPERIMENT: Experimental design

PARTNER	Tasks involved	Location experiments	Year beginning exp./Crop rotation/ Water regime	Main Treatments - Replications	Main Variables	MODELLING Model used
ARVALIS France	5.4	Oraison (Provence, Mediterranean region of France)	2013 Durum Wheat- Legumes (drought part) Rainfeed plots Durum wheat- Maize or soybean –legumes Irrigation plots	Living cover-crops (30 stripes of 900 m^2 without replications) No replications but experimental data is produced via the *Diagchamp method.*	Grain yield Crop/plant biomass Soil water content Soil properties	CHN

Fields experiment: Oraison (Provence, France)

Location	This field experiment was established in 2013 at Oraison (SE France, 43º 55' 51" N; 5º 55'25" E) in the Mediterranean part of France
General Climate	Temperate continental Mediterranean climate.
General Climate and Soil Description	Soil and climatic characteristics of the site are: General and soil (0–30 cm) characteristics of the field site. Soil properties were measured at the beginning of the experiment (October 2010). Elevation (masl) 377; Annual precipitation (mm). 650; Mean annual air temperature (◦C). 13.6°C; Annual PET (mm): 1343 Soil classification. Cambisol colluvic calcaric to the USDA classification (Soil Survey Staff, 2014) pH (H2O, 1:2.5) 8.6; Organic C (g kg−1) 30; Organic N (g kg−1) 1.9 Particle size distribution (%): Sand (2000–50 m) 14; Silt (50–2 m) 62; Clay (<2 m) 23
General description of experimental design, factor and levels of the factor.	A field of 0.4 ha at Drimos Thessaloniki, Greece was used for field experimentation in cooperation with a local farmer. Before setting up the experiments (June 2020) *Hordeum vulgare* was cultivated in the field by the farmer under Conventional tillage and was applied in all the previous years. The aim of the study was to evaluate the effect of conventional (CT) and minimum tillage (MT) on successive crops in a 3-year rainfed crop rotation and study their effect on crop yield. For this reason, the 0.4ha field was split into two adjacent field units each one of 0.2 ha, one for CT and the other for MT. CT mainly included ploughing and harrowing, whereas, MT mainly included soil harrowing. Seeding time and all the other field practices (eg. fertilization, and herbicides) were applied at the same time and the same rate in both CT and MT field units. Crop species in crop rotation included winter-sown crops such as legumes (*Lathyrus sativus*) and winter cereals (*Hordeum vulgare*) and also summer-sown crops such as *Panicum mileaceum* and *Sorghum bicolor*. *The experimental design*: The experimental field was vertically divided into two equal field units of the size 0.2 ha; one for CT and one for MT throughout the 3-year crop rotation. Both CT and MT field units were divided into four plots that were used as experimental blocks to assess the variance of the means resembling a randomized complete block design. Each plot of the CT was located next to the adjacent MT plot. However, due to the separate spatial arrangement of the plots (blocks) of each tillage system and due to the small (2) number of factors studied (Ct vs MT), data were analyzed with the t-test instead of ANOVA to check differences between conventional and minimum tillage. *The cropping system:* rainfed crop rotation, starting with *P. miliaceum* (June 2020), followed by *Lathyrus sativus (December 2020),* followed by *Sorghum bicolor* (June 2021), followed by *Hordeum vulgare* (November 2021) and ending with *Hordeum vulgare* (December 2022) in CT and MT adjacent field units. *Tillage systems:* Conventional Tillage (CT) (moldboard plough at 25 cm and power harrow at 5cm) vs Minimum Tillage (MT) (power harrow at less than 5 cm) in adjacent field units. In some cases, disc harrowing was also applied in CT, whereas for MT a soil loosener (Michel-tine) was also used occasionally. *Sowing:* All crops in crop rotation were direct-seeded with a mounted seed drill for power harrows (*Kvenerland Accord DA*). *Fertilization:* the fertilizers applied are reported separately for each crop; fertilization was similar for CT and MT *Harvesting:* All crops were hand-harvested by sampling

	Crop residue management: crop residues were soil incorporated under CT by ploughing at 25cm applied some days before sowing of the next crop followed by harrowing on seeding time with a power harrow. Crop residues under MT are left on the soil surface and harrowing was performed at a shallow depth (less than 5 cm) *Other operations, variables and observations:* Plant height, Leaf Area Index, crop biomass, N/P content, soil nutrient values, number of spikes, seed thousand weight and % seed protein content were measured. Other operations included recordings of dates for certain growth stages based on the BBCH scale. Weed counts and weed biomass were recorded in cases a weed management was necessary. 1-4 times per month depending on weather conditions soil samples from 0-20cm and 20-40cm depth were collected from both CT and MT fields to calculate the soil water content for the two soil depths. Weather data were collected from weather stations nearby.

HAO EXPERIMENT: Experimental design

PARTNER Country	Tasks involved	Location experiments	Year beginning exp./Crop rotation/ Water regime	Main Treatments - Replications	Main Variables	MODELLING Model used
HAO Greece	5.1; 5.2	Thessaloniki region	2019 2-year crop rotations Barley-Panicum miliaceum (winter) Lathyrous-Sorghum bicolor (summer) Rainfed	Intensive Tillage vs. Minimum Tillage Crop rotation 4 replications	Grain yield Crop plant/biomass Soil water content Nutrient soil analysis Weed species and weed density	NO

Field experiment in Drimos, Greece

Location	This field experiment was established in 2019 in Drimos (40°47'11, 22°57'53), close to Thessaloniki, north Greece.
General Climate	Temperate continental Mediterranean climate.
General Climate and Soil Description	Soil and climatic characteristics of the site are: Heavy soil with high clay content (48%), and neutral pH (7.4 both at 0-20 and 20-40 cm), rich in $CaCO_3$ (8.8% at 0-20cm, 11% at 20-40cm) and Organic matter content (3.0%) with normal level of salt (0.443 mS/cm at 0-20cm and 0.433 at 20-40cm). General and soil (0–30 cm) characteristics of the field site. Soil properties were measured in June 2021 before *Panicum miliaceum* seeding. Elevation (masl) 180 m; Annual precipitation (mm). 450 mm; Mean annual air temperature (◦C). 15.1 °C Soil classification. Entisols. According to the USDA classification (Soil Survey Staff, 2014) pH (H2O, 1:2.5) 7.35; EC1.5 (dS m−1) 0.443; Organic C (g kg−1) 2.96; Organic N (g kg−1) 10.08 Particle size distribution (%): Sand (2000–50 m) 30; Silt (50–2 m) 22; Clay (<2 m) 48
General description of experimental design, factor and levels of the factor.	A field of 0.4 ha at Drimos Thessaloniki, Greece was used for field experimentation in cooperation with a local farmer. Before setting up the experiments (June 2020) *Hordeum vulgare* was cultivated in the field by the farmer under Conventional tillage and was applied in all the previous years. The aim of the study was to evaluate the effect of conventional (CT) and minimum tillage (MT) on successive crops in a 3-year rainfed crop rotation and study their effect on crop yield. For this reason, the 0.4ha field was split into two adjacent field units each one of 0.2 ha, one for CT and the other for MT. CT mainly included ploughing and harrowing, whereas, MT mainly included soil harrowing. Seeding time and all the other field practices (eg. fertilization, and herbicides) were applied at the same time and the same rate in both CT and MT field units. Crop species in crop rotation included winter-sown crops such as legumes (*Lathyrus sativus*) and winter cereals (*Hordeum vulgare*) and also summer-sown crops such as *Panicum mileaceum* and *Sorghum bicolor*. The experimental design: The experimental field was vertically divided into two equal field units of the size 0.2 ha; one for CT and one for MT throughout the 3-year crop rotation. Both CT and MT field units were divided into four plots that were used as experimental blocks to assess the variance of the means resembling a randomized complete block design. Each plot of the CT was located next to the adjacent MT plot. However, due to the separate spatial arrangement of the plots (blocks) of each tillage system and due to the small (2) number of factors studied (Ct vs MT), data were analyzed with the t-test instead of ANOVA to check differences between conventional and minimum tillage. The cropping system*:* rainfed crop rotation, starting with *P. miliaceum* (June 2020)*,* followed by *Lathyrus sativus (December 2020),* followed by *Sorghum bicolor* (June 2021), followed by *Hordeum vulgare* (November 2021) and ending with *Hordeum vulgare* (December 2022) in CT and MT adjacent field units. Tillage systems*:* Conventional Tillage (CT) (moldboard plough at 25 cm and power harrow at 5cm) vs Minimum Tillage (MT) (power harrow at less than 5 cm) in adjacent field units. In some cases, disc harrowing was also applied in CT, whereas for MT a soil loosener (Michel-tine) was also used occasionally.

	<u>Sowing</u>: All crops in crop rotation were direct-seeded with a mounted seed drill for power harrows (*Kvenerland Accord DA*). *<u>Fertilization</u>:* the fertilizers applied are reported separately for each crop; fertilization was similar for CT and MT *<u>Harvesting</u>:* All crops were hand-harvested by sampling *<u>Crop residue management</u>:* crop residues were soil incorporated under CT by ploughing at 25cm applied some days before sowing of the next crop followed by harrowing on seeding time with a power harrow. Crop residues under MT are left on the soil surface and harrowing was performed at a shallow depth (less than 5 cm) *<u>Other operations, variables and observations</u>:* Plant height, Leaf Area Index, crop biomass, N/P content, soil nutrient values, number of spikes, seed thousand weight and % seed protein content were measured. Other operations included recordings of dates for certain growth stages based on the BBCH scale. Weed counts and weed biomass were recorded in cases a weed management was necessary. 1-4 times per month depending on weather conditions soil samples from 0-20cm and 20-40cm depth were collected from both CT and MT fields to calculate the soil water content for the two soil depths. Weather data were collected from weather stations nearby.

UdL-CSIC EXPERIMENT: Experimental design

PARTNER Country	Tasks involved	Location experiments	Year beginning exp./Crop rotation/Water regime	Main Treatments - Replications	Main Variables	MODELLING Model used
UdL- EEAD Spain	5.1; 5.2; 5.3; 5.4	Senes (Ebro Valley Region)	2010 Barley-Wheat-Pea. Rainfed	Tillage systems (2): No-til vs. Intensive tillage N fertilization (3) dose : 0, medium and high (2) type: mineral, organic. 3 replications	Grain yield Crop/plant biomass Soil water content Soil properties according to Task 5.3	NO

Field experiment in Senés de Alcubierre (Huesca, Spain)

Location	The field experiment was established in 2010 in Senés de Alcubierre (NE Spain, 41◦54’12” N; 0◦30’ 15” W) in a rainfed area
General Climate	Temperate continental Mediterranean climate.
General Soil description	Soil and climatic characteristics of the site are: General and soil (0–30 cm) characteristics of the field site. Soil properties were measured at the beginning of the experiment (October 2010). Elevation (masl) 395; Annual precipitation (mm) 327; Mean annual air temperature (◦C) 13.4; Annual PET (mm) 1197 Soil classification. Typic calcixerept. According to the USDA classification (Soil Survey Staff, 2014). pH (H2O, 1:2.5) 8.0; EC1.5 (dS m−1) 1.04; Organic C (g kg−1) 15.6; Organic N (g kg−1) 1.4 Particle size distribution (%): Sand (2000–50 m) 6.2; Silt (50–2 m) 63.3; Clay (<2 m) 30.5
General description of experimental design, factor and levels of the factor.	*The experimental design*: consisted of the combination of two tillage practices (CT, conventional tillage; NT, no-tillage) and three N fertilization rates (0, 75 and 150 kg N ha−1) based on two different types of fertilizer (mineral N and organic N with pig slurry) in a randomized block design with three replications. The plot size was 40 m × 12 m in the organic fertilization treatments and 40 m × 6 m in the mineral N fertilization and control treatments. *The cropping system* during the experiment consisted of a barley (Hordeum vulgare L., cv. Meseta) monocropping. The first four growing seasons. From the 2014-15 growing season a Pea-Barley-Wheat-Barley crop rotation has been following until date. *Tillage systems:* The CT treatment consisted of one pass of disk plough (15 cm depth) followed by a cultivator. However, due to the dry conditions of soil in 2011 two passes of chisel were used. A non-selective herbicide (1.5 L 36% glyphosate per hectare) was applied before sowing in the NT treatment. *Sowing:* Sowing was carried out with a no-till seeder equipped with disk-type furrow openers set to 2–4 cm depth. *Fertilization:* The combination of fertilizer types and N rates led to five fertilization treatments: 0, control,75 Min and 75 Org, 75 kg N ha−1with mineral and organic N at the beginning of tillering, respectively, and 150 Min and 150 Org,150 kg N ha−1with mineral and organic N applied at equal rates before sowing and at the beginning of tillering. For the mineral N treatments ammonium sulphate (21% N) and ammonium nitrate (33.5% N) were used before sowing and at the beginning of tiller-ing, respectively. Mineral N applications were performed manually. The organic fertilization treatment consisted of the application of slurry from fattening pigs of a commercial farm close to the site. The application was carried out by spreading the slurry with a commercial vacuum tanker fitted with a splashplate (Beguer mod. 12500, Barbastro, Spain) as it is common in the area. Previously to each application pig slurry was analyzed for its N content and the tanker was calibrated accordingly to apply the precise N rate. *Harvesting:* Harvesting of the plots was carried out with a commercial medium-sized combine. *Crop residue management:* Combine chopped and spread over the soil surface the crop residues.

	Other operations, variables and observations: Since the 1970s soil management at the site was based on the use of a subsoiler and a chisel. Four years before the establishment of the experiment (i.e. 2006) soil management was switched to NT. Daily air temperature and rainfall data were recorded with the use of an automated weather station located on the site and equipped with a data logger.

INRA EXPERIMENT: Experimental design

PARTNER Country	Tasks involved	Location experiments	Year beginning exp./Crop rotation/Water regime	Main Treatments - Replications	Main Variables	MODELLING Model used
INRA Morocco	5.1; 5.2; 5.3; 5.4	Merchouch	In 2020-21 Wheat (Durum wheat) Rainfed regime in semi-arid conditions In 2021-22 Wheat (Durum wheat) Rainfed regime in semi-arid conditions	Three factors tested Variety (5 Durum Wheat) Tillage: No-til vs. conventionnel tillage N Fertilisation dose: 35 N, 55 N, 75 N kg/ha) 3 replications Two factors tested Variety (4 Durum Wheat) Tillage: No-til vs. conventional tillage 3 replications	Grain yield Straw Yield WUE Soil parameters	AQUACROP/APSIM

Field experiment in Merchouch, Morocco

Location	The site is located at the Merchouch experimental station of the National Institute of Agronomic Research in Zaer, 60 km South of Rabat at 33°37 'N ; 6°43 'O
General Climate	Mediterranean climate with oceanic influence, with an average temperature of 28 ° C and an average rainfall equal to 350 mm.
General Soil description	Soil and climatic characteristics of the site are: The soil at the site is of the Vertisol type with a clay texture, a weakly developed structure and a relatively high OM content over the first ten centimetres of depth. General and soil (0–30 cm) characteristics of the field site. Elevation (masl) : 402 m; Annual precipitation (mm) 300; Mean annual air temperature (◦C). 19; Annual PET (mm): 1300 Soil classification. Vertisol. According to the USDA classification (Soil Survey Staff, 2014) pH (H2O, 1:2.5) 7,5; EC1.5 (dS m−1) 1,2; Organic C (g kg−1) 15,3; Organic N (g kg−1) 1,16 Particle size distribution (%): Sand (2000–50 m) 11,5; Silt (50–2 m) 23,3; Clay (<2 m) 55,2
General description of experimental design, factor and levels of the factor.	***The experimental design*:** **In 2020-21.** The experimental setup includes either ten treatments (two tillage types x three nitrogen doses x five durum wheat varieties). The experimental design was a randomized complete block with three replications. The two tillage types were conventional tillage (CT) and no tillage (NT). The three nitrogen doses were 20, 40, and 60 kg. ha^{-1}. The five varieties of durum wheat (Triticum durum Desf.) were Louiza (INRA-Morocco, 2011), Faraj (INRA-Morocco, 2007), and Nachit variety (INRA-Morocco 2017), as well as two new germplasms (M.G and I.C). *The cropping system:* Cereal/ food legume rotation: The experimentation was under a long-term comparative trial under cereal based system with two adjunct big plots (1Ha of plot under NT vs 1Ha of plot under CT). The 2 big plots had the same rotation (cereal-food legume). This year, we adopted the durum wheat (DW) as a crop to be studied. With 5 DW germplasm with different Nitrogen doses. *Tillage systems: Conventional tillage was completed using a disc harrow at 10 to 15 cm depth to prepare seedbeds and bury residues followed by a chisel plough. In no-tillage, the soil was loosened by 2 to 3 cm to plant the seeds at a depth of 5 cm, using a special no-tillage drill.* *Sowing:* late-November. Using NT direct seeder and CT seeder. *Fertilization:* 3 different Nitrogen fertilization doses (15+20 N, 15+40 N and 15+60 N). In fact, in the sowing period, the base fertilizer NPK 10-20-20 was applied at 150 kg ha−1 for all treatments. , and 2 months later, ammonium-nitrate 33.5% was supplied at a small plot to add an extra N dose of the selected doses (20, 40, and 60 kg. ha−1). The first fertilization occurs on the tillering stage with a rate of 35 N for all treatments and the second one occurs on the beginning of stem elongation where we add respectively, 20 N and 40 U for the 2 treatments. The 1st treatment did not receive any N fertilization (O N). *Harvesting:* In end-June using an experimental harvester. The Harsvet machine under NT was adapted to keep at least 30% of crop residue in the plot opposite to CT (No crop residues left on top soil as farmers practices).

	Crop residue management: Keeping 30 % of residues under NT and residues burial by tillage for CT *Other operations:* weed control; glyphosate before sowing and selective herbicide during the wheat cycle. **In 2021-22.** The experimental setup includes either ten treatments (two tillage types x four durum wheat varieties). The experimental design was a randomized complete block with three replications. The two tillage types were conventional tillage (CT) and no tillage (NT). The 4 varieties of durum wheat (Triticum durum Desf.) were Louiza (INRA-Morocco, 2011), Faraj (INRA-Morocco, 2007), as well as two new germplasms (M.G and I.C). *The cropping system:* Cereal/ food legume rotation: The experimentation was under a long-term comparative trial under the cereal based system with two adjunct big plots (1 ha of plot under NT vs. 1 ha of plot under CT). *Tillage systems: Conventional tillage was completed using a disc harrow at 10 to 15 cm depth to prepare seedbeds and bury residues followed by a chisel plough. In no-tillage, the soil was loosened by 2 to 3 cm to plant the seeds at a depth of 5 cm, using a special no-tillage drill.* *Sowing:* late November. Using NT direct seeder and CT seeder. *Fertilization:* in the sowing period, the base fertilizer NPK 10-20-20 was applied at 150 kg ha−1 for all treatments. , and 2 months later, ammonium-nitrate 33.5% was supplied (to reach 60 kg. Nha−1). *Harvesting:* In end-June using an experimental harvester. The harvest machine under NT was adapted to keep at least 30% of crop residue in the plot opposite to CT (No crop residues left on top soil as farmers practices). *Crop residue management:* Keeping 30 % of residues under NT and residues burial by tillage for CT *Other operations:* weed control; glyphosate before sowing and selective herbicide during the wheat cycle.

INRAT EXPERIMENT: Experimental design

PARTNER Country	Tasks involved	Location experiments	Year beginning exp./Crop rotation/Wateer regime	Main Treatments - Replications	Main Variables	MODELLING Model used
INRAT Tunisia	5.1; 5.2; 5.4	Kef site	2010 Three rotations - Monoculture: Durum Wheat - Biennial: Fava beans / Durum wheat; - Triennial: Fava beans / Durum wheat/Barley. Rainfed	Two factors experiment: Tillage: - CA: Conservation Agriculture. - CH: Chisel. - CO: Conventional tillage Rotation: - M: Monocroping. - Bi: Biannual rotation (Faba bean / Durum Wheat) - Tri: Triennal rotation: (Faba bean / / / Durum What) Three replications	Grain yield TKW Harvest Index (HI) Crop/plant biomass Soil water content WUE. Soil properties	APSIM

Field experiment in Kef Experimental Station of INRAT

Location	This field experiment was established in 2010 at Kef Experimental Station of INRAT (Western Tunisia) , (Long 36°07'58.01" N Lat 8°42'57.82"E, altitude= 520m)
General Climate	The Kef site, 5 km south of Kef City, is characterized by a medium semi-arid climate with a cold winter, an average annual rainfall of 450 mm and an annual mean temperature of 15,5°C
General Soil description	Soil and climatic characteristics of the site are: General and soil (0–30 cm) characteristics of the field site. Soil properties were measured at the beginning of trial implementation in 2010 Elevation (masl): 520 m; Annual precipitation (mm): 450 mm; Mean annual air temperature (◦C): 15.5 °C; Annual PET (mm): 950 mm Soil classification. Entisol pH (H2O, 1:2.5): 8.1; EC1.5 (dS m−1): 0.2; Organic C (g kg−1): 10; Organic N (g kg−1): 0.3 Particle size distribution (%): Sand (2000–50 m): 20%; Silt (50–2 m): 30%; Clay (<2 m): 50%
General description of experimental design, factor and levels of the factor.	*The experimental design*: This long-term trial combines three modes of soil tillage (main plot) and three rotation types (subplot) within a split-plot design. Three replications for each treatment are set up. *The cropping system:* Three rotation (monocropping, bi and trianual) . (i) monoculture: Durum Wheat (ii) biennial: Fava beans / Durum wheat; (iii) triennial: Faba beans/Durum wheat/Barley *Tillage systems:* (1) Conventional Tillage (CT): ploughing carried out by two plow coulters and mouldboard followed by an off-set sprayer, harrow and seed drill. (2) Minimum Tillage (MT): Working the soil with a chisel with rigid teeth followed by a Canadian cultivator with vibrating tines, a harrow and a seeder. (3) No-till (NT): Direct drilling in un-tilled soil with a disc drill without the previous removal of residues. *Sowing:* late November – early-Decembre. Using direct seeder *Fertilization:* DAP before sowing (100 kg.ha-1)+ ammonium nitrate (300 kg.ha-1) *Harvesting:* at maturity, mid-June using an experimental harvester *Crop residue management*: according to the treatments (retention of residues NT and residues burial by tillage for CT and MT) *Other operations, variables and observations*: weed control; glyphosate before sowing and selective herbicide during the wheat cycle. Variables to be measured: Yield and yield component, WUE, physiological; biomass evolution, N soil and plant content.

ENSA EXPERIMENTs: Experimental design

PARTNER Country	Tasks involved	Location experiments	Year beginning exp./Crop rotation	Main Treatments	Main Variables	MODELLING Model used
ENSA Algeria	5.1; 5.2; 5.4	Experiment S1: Algiers (North Algiers)	2018 Intercropping Chickpea/wheat vs. monocropping Rainfed	*Minimum Tillage* Under N fertilization Factors: 1)Cropping system (mono vs. intercropping) 2) N fertilizers (30, 60 and 100 kg N ha^{-1}) Rainfed conditions	Grain yield. Plant biomass. LAI. Soil water content. Plant water content. N uptake. Root depth and width Weed biomass Soil NO_3 and NH_4	These data will be used to run the CHN model or STICS
		Experiment S2: MEZLOUG (SETIF Center)	2018 Intercropping Chickpea/wheat vs. monocropping Rainfed	Conventional tillage under N fertilization Factors: 1)Cropping system (mono vs. intercropping) 2) N fertilizers (30, 60 and 100 kg N ha^{-1}) Rainfed conditions	Grain yield. Plant biomass. LAI. Soil water content. Plant water content. N uptake. Root depth and width Weed biomass Soil NO_3 and NH_4	These data will be used to run the CHN model or STICS

		Experiment S3: BAIDA BORDJ (South SETIF)	2018 Intercropping Chickpea/wheat vs. monocropping Rainfed	Conventional tillage under N fertilization Factors: 1)Cropping system (mono vs. intercropping) 2) N fertilizers (30, 60 and 100 kg N ha-^{1}) Rainfed conditions	Grain yield. Plant biomass. LAI. Soil water content. Plant water content. N uptake. Root depth and width Weed biomass Soil NO3 and NH4	These data will be used to run the CHN model or STICS

Field experiment in Algiers (North Algiers) – S1

Location	The experiment. is situated in the North of Algiers región (36°42′ N, 3°09′ E)
General Climate	Sub-humid climate
General Soil description	Soil and climatic characteristics of the site are: General and soil (0–30 cm) characteristics of the field site. Soil properties were measured at the sowing stage of each year experiment Elevation (masl): 40 m; Annual precipitation (mm). 450-500 mm; Mean annual air temperature (◦C). 19.55; Annual PET (mm): 1411 mm Soil classification. VERTISOLS pH (H2O, 1:2.5) 7.9; EC1.5 (dS m−1) 0.3 (dS cm); Organic C (g kg−1) 18; Organic N (g kg−1) 14 Particle size distribution (%): Sand (2000–50 m) 8; Silt (50–2 m) 35; Clay (<2 m) 57
General description of experimental design, factor and levels of the factor.	*The experimental design*: TWO FACTORS. Split plot with 3 replicates 1) Cropping system (mono vs intercropping) 2) N fertilizers (30, 60 and 100 U). Growing seasons: 2018/2019, 2019/2020 and 2020/2021 *Tillage system:* Minimum Tillage, working the soil with a cover crop followed by a harrow then a roller after the seed-drill *Sowing:* Sowing with a seed drill and intercrop chickpeas manually. Sowing was done in late November for the 2020/2021 season and mid-December for the 2018/2019 and 2019/2020 growing season *Fertilization:* 3 different fertilization doses (N-30 U, 60U and 100U). We used Urea spited in two times. The first fertilization occurs on the tillering stage with a rate of 30 U for all modalities and the second one occurs on the beginning of stem elongation where we add respectively 0 U, 30 U and 70 U for the three modalities. *Harvest:* At maturity on late May up to mid-June. *Crop residue management:* Crop residue was incorporated with tillage *Other operations, variables and observations:* Manual weeding without any treatment, cropping under rainfed conditions. Variables to be measured: Grain yield, Plant biomass. LAI. Soil water content. Plant water content. N uptake, Root depth and width, Weed biomass, Soil NO_3 and NH_4, STICS or CHN mode

Field experiment in Mezloug, Algeria - S2:

Location	The experiment is situated in Setif at MEZLOUGH región (center) at (36°06′ N, 5°20′ E).
General Climate	SEMI-ARID
General Soil description	Soil and climatic characteristics of the site are: General and soil (0–30 cm) characteristics of the field site. Soil properties were measured at the sowing stage in 2019 Elevation (masl) 951; Annual precipitation (mm). 280-300; Mean annual air temperature (◦C). 14.29; Annual PET (mm): 1524 Soil classification. VERTISOLS pH (H2O, 1:2.5) 8.38; EC1.5 (dS m−1) 0.26 dS cm; Organic C (g kg−1) 12; Organic N (g kg−1) 1.4 Particle size distribution (%): Sand (2000–50 m) 21; Silt (50–2 m) 36; Clay (<2 m) 43
General description of experimental design, factor and levels of the factor.	*The experimental design*: TWO FACTORS. Split plot with 3 replicates 1) Cropping system (mono vs intercropping). 2) N fertilizers (30, 60 and 100 U) Growing seasons: 2018/2019, 2019/2020 and 2020/2021 *Tillage system:* Minimum Tillage, working the soil with a cover crop followed by a harrow then a roller after the seed-drill *Sowing:* Sowing with a seed-drill and intercrop chickpeas manually. Sowing was done in late November for the 2020/2021 season and mid-December for the 2018/2019 and 2019/2020 growing season *Fertilization:* 3 different fertilization doses (N-30 U, 60U and 100U). We used Urea spited in two times. The first fertilization occurs on the tillering stage with a rate of 30 U for all modalities and the second one occurs on the beginning of stem elongation where we add respectively 0 U, 30 U and 70 U for the three modalities. *Harvest:* At maturity on late May up to mid-June. *Crop residue management:* Crop residue was incorporated with tillage *Other operations, variables and observations:* Manual weeding without any treatment, cropping under rainfed conditions. Variables to be measured: Grain yield, Plant biomass. LAI. Soil water content. Plant water content. N uptake, Root depth and width, Weed biomass, Soil NO3 and NH4, STICS or CHN model

A field experiment in Baida Bordj (Setif, Algeria) – S3

Location	The Baida Bordj experiment (955 m) (35°53′ N, 5°39′ E) is located in the South of the Setif region.
General Climate	SEMIARID CLIMATE
General Soil description	Soil and climatic characteristics of the site are: General and soil (0–30 cm) characteristics of the field site. Soil properties were measured at the sowing stage in 2019 Elevation (masl) 1000 m; Annual precipitation (mm). 180-220 mm; Mean annual air temperature (◦C). 15.11; Annual PET (mm): 1719 Soil classification. VERTISOLS pH (H2O, 1:2.5) 8.30; EC1.5 (dS m−1) :0.27; Organic C (g kg−1) 19 g Kg; Organic N (g kg−1) 2.4 g Kg Particle size distribution (%): Sand (2000–50 m) 16; Silt (50–2 m) 34; Clay (<2 m) 50
General description of experimental design, factor and levels of the factor.	*The experimental design*: TWO FACTORS. Split plot with 3 replicates 1) Cropping system (mono vs intercropping) 2) N fertilizers (30, 60 and 100 U) Growing seasons: 2018/2019, 2019/2020 and 2020/2021 *Tillage system:* Minimum Tillage, working the soil with a cover crop followed by a harrow then a roller after the seed-drill *Sowing:* Sowing with a seed-drill and intercrop chickpeas manually. Sowing was done in late November for the 2020/2021 season and mid-December for the 2018/2019 and 2019/2020 growing season *Fertilization:* 3 different fertilization doses (N-30 U, 60U and 100U). We used Urea spited in two times. The first fertilization occurs on the tillering stage with a rate of 30 U for all modalities and the second one occurs on the beginning of stem elongation where we add respectively 0 U, 30 U and 70 U for the three modalities. *Harvest:* At maturity in late May up to mid-June. *Crop residue management:* Crop residue was incorporated with tillage *Other operations, variables and observations:* Manual weeding without any treatment, cropping under rainfed conditions. Variables to be measured: Grain yield, Plant biomass. LAI. Soil water content. Plant water content. N uptake, Root depth and width, Weed biomass, Soil NO3 and NH4, STICS or CHN model

Annex 2. Network of field experiments: Methodology for soil water content, water use and water use efficiency

Variable	Methodology
Soil water content, Water use and Water use efficiency	CREA: Experiment 1 started in 2013: in previous years we measured soil moisture content with the gravimetric method; we collected 3 sampling per elementary plot at 0-20 and 21-40 cm soil depth (fresh and then dried in oven at 105 °C) at several times during the season; we'll be able to collect them in winter-spring 2021. Experiment 2 started in 2002: volumetric soil water content (gravimetric soil water content * bulk density) from 2016 onwards, at 0-10 cm depth. Soil moisture at 0-5 cm (with WET-2 Delta T © probe) and 0-30 cm (with the gravimetric method) at sowing and harvest ARVALIS: Soil water content is measured by Tensiometers (watermark type) HAO: In the experiment samples from 2 soil depths (0-20 & 20-40 cm) at several times (gravimetric content). Meteorological stations with data logging remote access, which includes rainfall and soil moisture sensors will be installed in the trials. Calculation of WU (%) and WUE (Kg/mm/ha) are done by estimation of reference evapotranspiration (ETo) was estimated using the ASCE-standardized method (Allen et al., 1998;2005), while real evapotranspiration (ETa) was estimated using water balance simulations with the AQUACROP model1. The calibration of the model was made using soil moisture measurements. The amount of rainfall, the real evapotranspiration ETa and the yields of MT and CT treatments were used to estimate the parameters of Water Use (WU) and Crop Water Crop Use Efficiency (CWUE or WUE). The estimation of ETo using the ASCE-standardized method is performed by the following equation (Allen et al. 2005):

	$$ET_o = \frac{0.408\Delta\left(R_n - G\right) + \dfrac{\gamma u_2 (e_s - e_a) C_n}{\left(T_{\text{mean}} + 273.16\right)}}{\Delta + \gamma(1 + C_d u_2)} \qquad (1)$$ where ETo is the reference crop evapotranspiration (mm d^{-1}), Rn is the net solar radiation at the crop surface (MJ m^{-2} d^{-}1), u2 is the wind speed at 2 m height above the soil surface (m s^{-1}), Tmean is the mean daily air temperature (oC), G is the soil heat flux density at the soil surface (MJ m^{-2} d^{-1}), as is the saturation vapor pressure (kPa), ea is the actual vapor pressure (kPa), Δ is the slope of the saturation vapor pressure-temperature curve (kPa $^{o}C^{-1}$), γ is the psychrometric constant (kPa $^{o}C^{-1}$), Cn and Cd are constants, which vary according to the time step and the reference crop type and describe the bulk surface resistance and aerodynamic roughness. The short reference crop (ASCE-short), which is used in this study, corresponds to clipped grass of 12 cm height and surface resistance of 70 s m^{-}1 where the constants Cn and Cd have the values 900 and 0.34, respectively. (Allen et al., 2005). The use of Eq.1 at the daily or monthly step for short reference crop is equivalent to the FAO-56 method (Allen et al., 1998). Taking into account the amount of precipitation and the amount of ETa Water Use (WU) was computed using the following equation (2): WU (%) = (Wu/Wd) x 100 (2) where, WU= water beneficially used = ETa Wd= water delivered= Precipitation Crop Water Use Efficiency (CWUE) was computed according to the following equation (3): CWUE= Y/ ETa (3) where, Y= observed crop yield UDL-CSIC: In the experiment soil water content is measured previous to sowing, starting tillering and after harvest soil samples from each plot (2 observations) at two depths 0-30 and 30-60 cm are taken. Soil water content is determined in the lab by gravimetric method. A simple water balance with rainfall and soil water variation and yield will allow us to calculate WU and WUE. Runoff and drainage are considered ineligible dua a non-percolant water regime-

	INRAT: In the experiments soil water content will be monitored during the growing season for 3 soil layers (0-20 cm, 20-40 cm and 40-60 cm), in order to determine the water balance and ETR that will be used for the calculation of WUE. Water use efficiency (WUE in kg ha^{-1} m^{-3}) was calculated as the ratio between grain yield and the real evapotranspiration (ETR in mm). The soil water content was determined by gravimetry at sowing and maturity of durum wheat. The real evapotranspiration (ETR) of the crop was calculated based on a simplified the water balance method. Water balance = soil water content at sowing + precipitation during the growing season - soil water content at harvesting. INRA. In the experiment that started in 2004. Soil moisture content was measured during all cropping seasons with gravimetric method. Since the CAMA project started, samples were collected randomly (3 samples per plot at 0-15, 15-30 cm and 30-45 cm soil depth). Samples were measured in the field and then dried in an oven at the soil lab (at 105 °C) 3 times during the season (at sowing, tilling and at harvesting). For WU and WUE, we used a water balance method (Soil Water (at sowing)+Rainfall (Nov-June) - Soil Water (at harvesting)) and the grain yield. ENSA: In the experiments different measurements were done as follows: Water content measurement in Exp 1: Site OUED SMAR (subhumid conditions): Soil moisture (at each 10 cm depth) was regularly measured by a soil probe (Diviner 2000, Sentek Pty Ltd, United States of America) for all plots with one observation per plot on a daily basis. The collected soil moisture values (in scaled frequency unit) from the probe measurements were calibrated (i.e. volumetric soil water content in m3 m-3 unit) according to methods reported by Groves and Rose (2004) and Haberland et al. (2014). Water content measurement in Exp 2 and 3: Site Mezlough and Baida Bordj (semiarid conditions): The oven-drying method was performed to measure soil moisture (at 0–20 and 20–40 cm). The soil is sampled and transferred into a container, weighed under the sampled condition, oven dried, and weighed again after drying (at 105-110°C). All soil measurements were established within 4 replicates (laboratory) where each replicate corresponds to one composite sample taken from each treatment (four sub-plots). Finally, the volumetric water content (m3 m-3) was estimated by multiplying the bulk soil density by the measured gravimetric moisture. **Water use (WU) and Water use efficiency (WUE) measurements:** The seasonal evapotranspiration (ET) of each cropping system was calculated using the water balance equation ***ET= P + I + U – R – Dw – ΔS;*** which is based on the calculation of volumetric water content at

	sowing (initial soil moisture) and during the different cropping (i.e. sowing, flowering and harvest) stage [43] Here P is the rainfall amount (mm) cumulated from the sowing to harvest period, R is the water amount relative runoff and which was negligible in our field conditions. I represent the amount of irrigation applied during the cropping cycle (I=0, no applied irrigation overall cropping seasons). U and Dw are defined respectively as the upward and downward capillary flow into the rooting area, the values of U and Dw are considered as negligible in the case of our field experiment conditions. ΔS is the change of soil volumetric moisture (converted in mm) at the soil layer from 0 to 40 cm (soil depth of experiment site), it was calculated from the difference between soil moisture measured in both initial soil and harvested soil at the crop maturity. Additionally, the WUE of each crop was assessed relative to grain yield (WUEGY) of wheat and chickpea monoculture and for mixed crops. As that, WUE by grain yield in each cropping system (WUEGY) was calculated (Eq. 5) as the ratio between ET (WU) and grain yield [22]. In the intercropping case, WUE was calculated by using both mixed grain yields of the two intercropped species. NUE was also assessed in each crop-syst*N-level treatment and compared across the four years of the field experiment. Calculation was principally performed according to the fertilizers-based approach, in which NUE is defined as the rate of N fertilizer that was utilized and allocated to corresponding N grain yield N [44]. Hence, NUE was determined by calculating the ratio between N grain yield and the corresponding rate of applied N-fertilizer (Eq. 6). However, the NUE calculation in the intercropping system was done by using the mixed N grain yield of both intercropped species.