

INFLUENCE OF DIFFERENT IRRIGATION REGIMES ON COVER CROPS BIOMASS PRODUCTION AND WATER PRODUCTIVITY

INFLUENCE DE DIFFÉRENTS RÉGIMES D'IRRIGATION SUR LA PRODUCTION DE BIOMASSE DES CULTURES DE COUVERTURE ET LA PRODUCTIVITÉ DE L'EAU

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ABSTRACT

Cover crops provide important ecosystem services but their establishment and biomass production are often constrained by water availability under Mediterranean conditions. This study investigated the effects of contrasting irrigation regimes on cover crop biomass production, soil water dynamics, and water productivity during the 2025–2026 growing season in southern France. A double cover crop system combining a summer sorghum/vetch mixture followed by a winter rapeseed/phacelia/faba bean mixture was evaluated under three irrigation treatments: rainfed (IR0), 20 mm irrigation at sowing (IR), and 150 mm supplemental irrigation (IR+). Soil water content was monitored biweekly down to 1.5 m using neutron probe measurements, allowing calculation of cover crop water use through a field-scale water balance approach.

Irrigation strongly increased summer cover crop biomass production, reaching 0.3, 1.9, and 6.0 t DM ha⁻¹ under IR0, IR, and IR+, respectively. Corresponding water use amounted to 31, 87, and 180 mm. Total water productivity increased with irrigation, while irrigation water productivity was highest under the single establishment irrigation treatment. Results highlight that limited irrigation at establishment may provide an efficient compromise between biomass production and water conservation under Mediterranean semi-arid conditions.

Keywords: Biomass production; Water productivity; Ecosystem services; Soil water dynamics; Water use.

RESUME

Les cultures de couverture fournissent des services écosystémiques importants, mais leur mise en place et la production de biomasse font souvent face aux contraintes de la disponibilité de l'eau dans les conditions méditerranéennes. Cette étude a examiné les effets exercés par les régimes d'irrigation contrastés sur la production de biomasse des cultures de couverture, la dynamique de l'eau dans le sol et la productivité de l'eau au cours de la saison de croissance 2025–2026 au sud de la France. Un système à double culture de couverture, en combinant un mélange de sorgho et de vesce en été avec un mélange de colza, de phacélie et de féverole en hiver, a été évalué selon trois traitements d'irrigation : agriculture pluviale (IR0), avec 20 mm d'irrigation au semis (IR) et avec 150 mm d'irrigation d'appoint (IR+). Le suivi de la teneur en eau du sol a été réalisé toutes les deux semaines jusqu'à une profondeur de 1,5 m à l'aide de mesures par sonde à neutrons, permettant ainsi de calculer la consommation de l'eau par des cultures de couverture grâce à une approche de bilan hydrique à l'échelle de la parcelle. L'irrigation a fortement accru la production de biomasse des cultures de couverture en été, atteignant 0,3, 1,9 et 6,0 t MS ha⁻¹ respectivement dans le cadre de traitements IR0, IR et IR+. La consommation d'eau correspondante s'élevait à 31, 87 et 180 mm. La productivité totale de l'eau a augmenté avec

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l'irrigation, tandis que la productivité de l'eau d'irrigation était la plus élevée dans le traitement d'irrigation dans un établissement unique. Les résultats soulignent qu'une irrigation limitée dans un établissement peut constituer un compromis efficace entre la production de biomasse et la conservation de l'eau dans des conditions semi-arides méditerranéennes.

Mots-clés : Production de biomasse; Productivité de l'eau; Services écosystémiques; Dynamique de l'eau du sol; Consommation d'eau.

INTRODUCTION

Climate change is placing increasing pressure on agricultural systems through the intensification of the hydrological cycle, leading to more frequent and severe extreme events such as intense rainfall and prolonged drought periods. Because cover crops directly interact with soil and water processes, they may help buffer some of these hydrological impacts. This issue is particularly critical in Mediterranean and semi-arid environments, where water availability strongly constrains crop production (Dominguez-Bohorquez et al 2025, Lee et al 2019).

In field crops systems, cover crops can effectively reduce both wind and water erosion, which is frequently identified as one of the main drivers of their adoption by farmers (Golden et al 2023). By protecting the soil surface from raindrop impact, cover crops help preserve soil structure, enhance aggregate stability, and maintain favorable infiltration conditions (Haruna et al. 2018, Kaspar et al. 2001). In addition, cover crops provide fresh organic matter inputs that stimulate soil biological activity and contribute to maintaining soil porosity.

Beyond their effects on erosion and infiltration processes, cover crops influence several components of the hydrological cycle at the field scale. While they can improve rainfall infiltration and potentially reduce runoff, they also increase soil water losses through evapotranspiration and may therefore reduce the amount of soil water available for the subsequent cash crop (Zhang et al. 2023). Consequently, cover crops may simultaneously provide important hydrological services and generate potential disservices depending on climatic conditions and management practices. It therefore appears essential to better understand how cover crops influence soil water dynamics and hydrological fluxes at the field scale in order to identify agronomic practices capable of maximizing ecosystem services while limiting potential disservices.

Several meta-analyses have investigated the effects of cover crops on the hydrological cycle and soil water dynamics as influenced by soil type, climate, and cover crop species composition. For example, Wang et al. 2021 showed that, overall, cover crops tend to decrease soil moisture across the entire soil profile while increasing water content within the upper 30 cm of the soil. Their results also highlighted contrasting effects on subsequent crop yields, with neutral to negative responses in arid and semi-arid climates and generally positive effects in humid conditions.

Similarly, Gabra et al. 2022 identified an annual precipitation threshold around 700 mm below which cover crops were more likely to induce yield penalties in subsequent cash crops. They also highlighted the critical role of management, showing that delayed cover crop termination substantially reduced soil water content, although this additional depletion did not systematically translate into lower yields.

Although these studies provide valuable insights into the overall effects of cover crops on the soil water balance, they generally do not describe in detail the temporal dynamics of rainfall events, soil water recharge and depletion phases, or short-term hydrological processes. Consequently, they do not fully explain how hydrological dynamics interact with cover crop management practices, limiting the ability to identify agronomic strategies capable of maximizing ecosystem services while minimizing potential disservices.

Some studies have investigated the effects of cover crops on soil water dynamics using continuous soil moisture monitoring approaches. For instance, Roberts et al. (2026) monitored soil water tension and reported improved soil water status under all cover crop treatments compared with a no-cover-crop

control. These improvements resulted in a significant reduction in irrigation requirements for the subsequent cotton crop. Similar results were reported by Paye et al. (2021) in a semi-arid corn silage production system. Using capacitance probes installed down to 1 m depth, the authors monitored weekly variations in volumetric soil water content.

They observed lower soil water content in all cover crop treatments at cover crop termination compared with the no-cover crop treatment. However, during the subsequent corn growth phase, soil water content progressively increased under cover crop treatments, which was attributed to improved infiltration of rainfall and irrigation water as well as enhanced water retention due to surface residue cover. However, most of these studies focus primarily on rainfed systems and rarely quantify cover crop water use directly. Existing estimates suggest substantial variability depending on species and management, with cover crop water use ranging from 73 mm under early termination to 188 mm under late termination (Zhang et al., 2023).

The studies cited so far provide valuable understanding of how cover crops affect soil water balance in rainfed systems. However, the very low soil moisture conditions occurring during the hot and dry summers of the Mediterranean basin make it difficult to establish summer cover crops and even more difficult to achieve biomass levels sufficient to provide the targeted ecosystem services. In this context, irrigation has been investigated as an adaptive strategy for cover cropping under semi-arid conditions. Previous studies reported contrasted effects of irrigation on cover crop biomass production, with increases ranging from 0% to 58% depending on climatic conditions and management practices (Rouge et al., 2022; Agarwal et al., 2022; Nielsen et al., 2015). However, these studies generally do not provide detailed information regarding the effects of irrigation on soil water dynamics or cover crop water use.

Therefore, this study aims to investigate at field scale how irrigation management may support cover cropping under Mediterranean conditions, with a particular focus on (i) soil water balance dynamics throughout the cover crop cycle, (ii) cover crop water use under contrasting irrigation regimes, and (iii) biomass production and water productivity responses to irrigation.

MATERIALS AND METHODS

Experimental site and cover crop experiment

This study was conducted during the 2025-2026 growing season at the Centre INRAE Occitanie-Montpellier Lavalette Research Station. The soil type is loam-clay soil with low stone content. The study focuses on the fallow period following a winter barley cash crop harvested on June 20th 2025 and investigated a long-term double cover crop (CC) system combining summer and winter cover crops.

After soil tillage, a first sorghum/vetch mixture (summer CC) have been sown on July 23th 2025 (3cm depth, 15cm row spacing, at a rate of 20 kg/ha and 40 kg/ha respectively) while a succeeding rapeseed/phacelia/winter faba beans mixture (winter CC) have been direct seeded into the sorghum/vetch mixture on October 14th 2025 (3cm depth, 15cm row spacing, at a rate of 2 kg/ha, 3 kg/ha and 200 kg/ha respectively). The summer sorghum component was naturally terminated by frost on November 19th 2025 while vetch remained throughout the experiment. Final termination date of the CC experiment occurred on April 22nd 2026. No fertilisers or herbicides were applied.

Experimental design and irrigation treatments

The experiment was laid out as a split-plot design with three replications arranged in 6x6m plots. The main plot factor was cover crop mixture and the split plot factor consists of three levels of irrigation: rainfed (**IR0**), 20mm irrigation only at seeding (**IR**), 150mm (~5x30mm) irrigation to meet plant's need (**IR+**). After sowing, the first irrigation for IR+ treatment occurred on August 13th 2025. Between July 23th 2025 (sowing) and October 14th 2025 (summer CC termination), CC received 43mm of rain but no rain occurred before August 20th. Randomization of irrigation at the plot scale has been achieved using a network of 40mm PE irrigation pipes supplying PJG Hunter 04 sprinklers (17mm/h) at the four corners of each plot. In each IR+ plots, Watermark tensiometers have been inserted into the soil to depths of

30cm and 60cm to monitor soil water tension. 30mm irrigation was triggered on IR+ treatments when soil water tension went below a threshold of -80kPa at 30cm the first month of the experiment and -80 kPa at 60cm afterwards. No irrigation occurred after October 14th 2025, so that winter CC received no supplemental irrigation while they received 868mm of rain with heavy downpour as much as 140mm a day.

Soil water monitoring and cover crop water use

On a biweekly basis soil water content was measured in 0.1 m intervals down to 1.5m at each plot using a neutron probe (Model 503 Elite hydroprobe, InstroTek Inc.). The neutron probe was calibrated against gravimetric soil water samples taken at different time of the year to ensure calibration under dry and wet condition. Dynamic water uptake by CC was calculated from the water balance as the difference between soil water readings dates plus rain and irrigation. Precipitation amounts have been tracked with an automated weather station. Since the field is flat and visual observations following heavy rain events did not show signs of runoff, the latter has been considered negligible. Due to heavy rain at some dates during winter, evidence of deep percolation has been detected via neutron probes readings. Therefore, water uptake by CC has been calculated only when neutron readings showed a soil moisture below field capacity, which ensures no deep percolation.

Biomass measurements and water productivity

At cover crop termination, aboveground biomass was sampled using three 0.5 m² quadrats per plot. Plant species were sorted and weighed for fresh biomass. A subsample of approximately 400 g was taken for each species, oven-dried at 70°C for 48 h, and then weighed to determine dry biomass. The fresh-to-dry biomass ratio obtained from the subsamples was used to estimate the total dry biomass production per hectare for each plot.

Total water productivity has been calculated as the ratio between dry weight biomass at termination and CC water use (taking into account rain + irrigation) from sowing to termination. First neutron reading occurred on August 7th 2025, two weeks after sowing but water uptake by CC at such early stage is assumed negligible for summer CC WUE calculation. Because deep percolation occurred during winter, it has not been possible to determine winter CC total water productivity.

Irrigation water productivity, defined as the supplemental dry matter produced thanks to irrigation compared to rainfed treatment, has also been calculated.

RESULTS

Soil water balance and cover crop water use

The soil water balance makes it possible to understand how soil water storage evolves over time. It is composed of three main components: water inputs (rainfall and irrigation), water storage (soil water content), and water outputs, including evapotranspiration, runoff, and drainage. In the present experiment, runoff was considered negligible, while periods during which drainage occurred were excluded from water use calculations. Figure 1 illustrates the temporal dynamics between soil water storage, water inputs through rainfall and irrigation, and water losses associated with cover crop evapotranspiration.

Figure 1.a) shows the evolution of soil water content over time. The graph is divided into two main periods: the summer cover crop growing period, highlighted in light orange, and the winter cover crop growing period, highlighted in light green.

Three main phases can be distinguished. From 07/08 to 04/11, the soil underwent a drying phase, during which water consumption by the summer cover crop exceeded water recharge from rainfall and irrigation. From 04/11 to 12/03, a soil recharge phase was observed, with rainfall progressively replenishing the soil water reserve up to field capacity. During this period, water inputs from rainfall

exceeded water consumption by the winter cover crop. Finally, from 12/03 to 23/04, the soil entered a new drying phase, in which water consumption by the winter cover crop again exceeded water recharge from rainfall.

For the summer cover crop period, no significant differences in soil water storage were observed between treatments. However, the IR treatment tended to induce slightly greater soil drying compared with the other treatments.

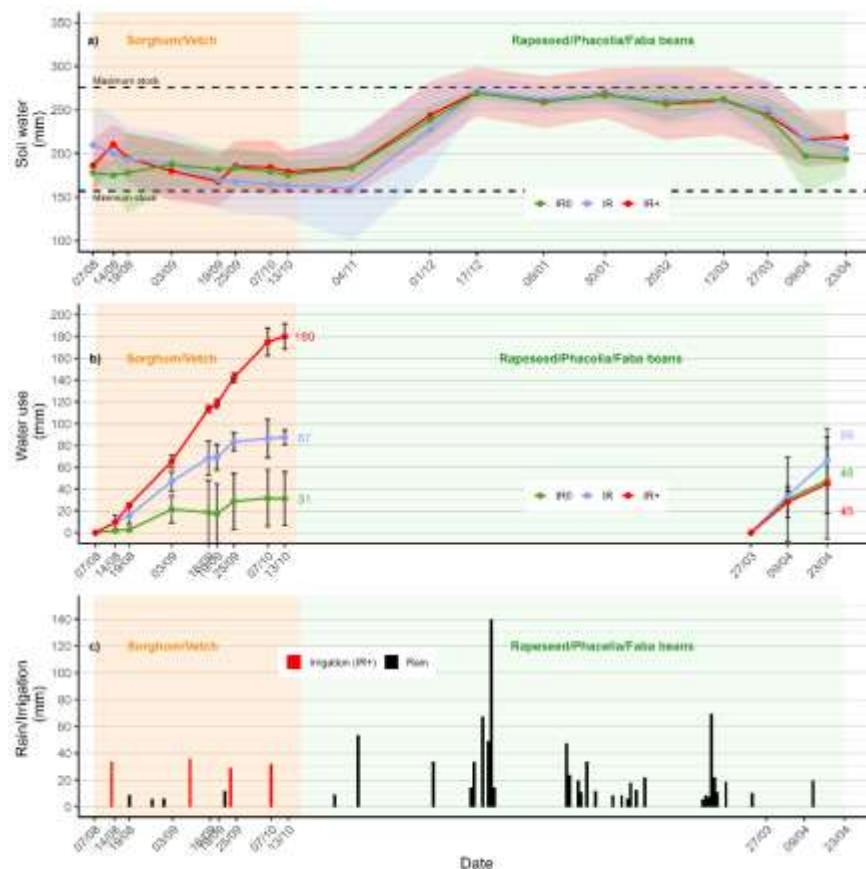


Figure 1. Temporal variations of the main field water balance components during the experiment: a) soil water storage (mm); b) cumulative cover crop water consumption (mm), corresponding to evapotranspiration losses; and c) rainfall and irrigation inputs (mm). Dashed lines indicate the minimum and maximum soil water storage values observed across all treatments within the 0–90 cm soil profile.

During the winter cover crop period, the soil water deficit previously observed under the IR0 treatment was progressively compensated by rainfall recharge and had disappeared by 17/12. Thereafter, soil water content remained close to field capacity until 12/03 due to substantial rainfall inputs. During this period, the cover crop had little influence on soil water content, as water recharge largely compensated for cover crop water consumption. From 27/03 onward, the soil entered a new drying phase. No significant differences in soil water storage were observed between treatments, although the IR0 treatment again tended to dry the soil slightly faster than the other treatments.

Figure 1.b presents the cumulative water consumption of the cover crops (mm) over time from the cover crop perspective. Water consumption was calculated from 07/08 to 13/10 for the summer cover crop and from 27/03 to 23/04 for the winter cover crop. It should be noted that cumulative water consumption values are only valid between two consecutive measurement dates and do not necessarily represent the total water consumption of the cover crop over its entire growing period. For the summer cover crop, the calculated cumulative consumption corresponds to the total water consumption over the monitored

period. In contrast, for the winter cover crop, water consumption could not be calculated between 17/12 and 27/03 due to drainage events. Consequently, the cumulative consumption displayed for the winter cover crop only represents water consumption during the beginning of spring period, between 27/03 and 23/04.

For the summer cover crop, significant differences in cumulative water consumption were observed between treatments. As expected, the IR+ treatment showed the highest water consumption (180 mm), followed by the IR treatment (87 mm), while the IR0 treatment exhibited the lowest consumption (31 mm). When examining the consumption dynamics, each water input event, whether rainfall or irrigation (Figure 1.c), resulted in an increase in the rate of water consumption by the cover crop. This observation is consistent with Figure 1.a, which shows that soil water storage remained close to its minimum level throughout most of the summer cover crop period. Despite substantially greater water use under IR+, soil water storage remained close to minimum levels during most of the summer period, providing no evidence of over-irrigation. Rather, irrigation appeared to sustain active cover crop growth under otherwise highly limiting moisture conditions.

For the winter cover crop, no significant differences in water consumption were observed between treatments. Over the calculation period, from 27/03 to 23/04, the IR0, IR, and IR+ treatments consumed 45, 48, and 66 mm of water, respectively, at a relatively continuous rate. It is noteworthy that, within only one month, the winter cover crop consumed nearly half of the available soil water reserve.

Daily water use dynamics of summer cover crops

In an operational decision-making context for determining irrigation water requirements for cover crops, it is also useful to estimate daily water use. Figure 2 shows the daily water use of the summer cover crop for the IR0, IR, and IR+ treatments over the period from 07/08 to 13/10. On 07/08, approximately 20 days after sowing, IR and IR+ exhibited similar water use, around 1.4 mm d⁻¹, whereas IR0 showed a much lower value of approximately 0.3 mm d⁻¹. Thereafter, IR0 and IR displayed temporal variations in water use driven by successive soil wetting and drying cycles. Overall, IR showed an average water use about 1 mm d⁻¹ higher than IR0 over the period.

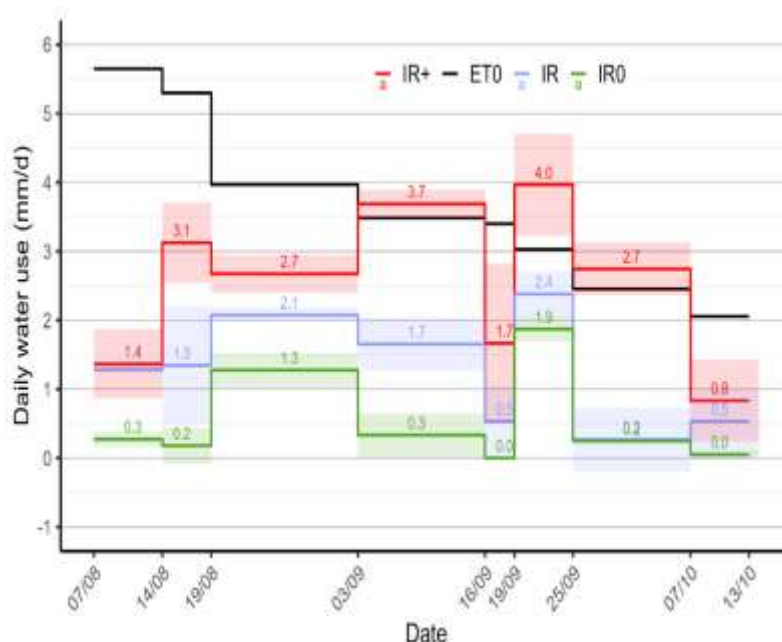


Figure 2. Variation over time of cover-crop daily water use (mm/d), under 3 different irrigation regimes IR0, IR and IR+. Daily water use is compared to reference evapotranspiration (ET0). The shaded envelopes represent the 95% confidence intervals.

In contrast, IR+ exhibited an increasing trend, reaching up to 4 mm d⁻¹ between 03/09 and 25/09. Temporary declines in water use were nevertheless observed during specific periods (between 19/08 and 3/09 and between 16/09 and 19/09), likely reflecting transient water stress due to insufficient irrigation between irrigation events. These findings suggest that, even under high irrigation supply, summer cover crops remained sensitive to short-term water limitations under Mediterranean summer conditions.

Total dry biomass produced and water productivity

Summer cover crop: At summer CC termination, mean total aboveground biomass, expressed in t DM.ha⁻¹ (t dry matter.ha⁻¹), produced by IR0, IR and IR+ treatments is of 0.3 ± 0.2, 1.9 ± 0.6 and 6.0 ± 2.2 respectively. Results indicates that irrigation allowed 533% and 1 900% increase in total aboveground biomass production compared to rainfed for **IR** and **IR+** treatments respectively.

During the growing window, **IR0**, **IR** and **IR+** treatments consumed 31 mm, 87 mm and 180 mm of water respectively (Figure 1b). This led to a total water productivity (dry matter produced by total water received (rain + irrigation)), expressed in DM.mm⁻¹ (t dry matter.mm⁻¹), of 10 ± 7 kg DM.mm⁻¹, 21 ± 6 kg DM.mm⁻¹ and 33 ± 12 kg DM.mm⁻¹ respectively. When we look at irrigation water productivity only (supplemental dry matter produced thanks to irrigation compared to rainfed treatments), water productivity amounts to 78 ± 28 kg DM.mm⁻¹ and 38 ± 14 kg DM.mm⁻¹ for **IR** and **IR+** treatments respectively.

Winter cover crop: At winter CC termination, mean total aboveground biomass, expressed in t DM ha⁻¹ (t dry matter ha⁻¹), produced by IR0, IR and IR+ treatments is of 7.0 ± 0.4, 7.1 ± 0.7 and 6.9 ± 0.7 respectively. It should be noted that IR0, IR, and IR+ refer to the irrigation treatments applied to the summer cover crop; the winter cover crop was not irrigated. Because of drainage during winter, no determination of water productivity could be made.

DISCUSSION

Biomass production

Increasing irrigation strongly enhanced summer cover crop biomass production, with biomass increasing by 533% and 1,900% under IR and IR+, respectively, compared with the rainfed IR0 treatment. These responses largely exceeded the biomass gains previously reported in the literature, which generally ranged from 0% to 58% under irrigated cover cropping systems (Rouge et al. 2022, Agarwal et al. 2022, Nielsen et al. 2015).

In contrast, no carry-over effect of summer irrigation treatments was observed on winter cover crop biomass production, with all treatments producing approximately 7 t DM ha⁻¹. Despite the higher summer biomass under IR+, probable nutrient depletion did not appear to limit winter cover crop development, likely because the winter mixture was dominated by legumes (faba bean and vetch).

Cover-crop water use

Summer cover crop: In our study, the rainfed treatment (IR0) used only 31 mm of water (fig 1b), which is substantially lower than the 188 mm reported for a rainfed sorghum cover crop in Zhang et al. (2023). However, direct comparison remains difficult because biomass production was not reported in their study and rainfall inputs reached 208 mm, suggesting substantially less water-limited conditions than those observed in our experiment. Under the extremely dry summer conditions of our study, the IR+ treatment therefore likely provides a more relevant comparison. Overall, these results suggest that approximately 180 mm of water may be required for a sorghum cover crop to approach its full biomass production.

Winter cover crop: It is noteworthy that, within only one and a half months (between 12/03 and 23/04), the winter cover crop consumed nearly half of the available soil water reserve. These findings reinforce

previous concerns regarding trade-offs between ecosystem services provided by cover crops and competition for soil water under water-limited conditions Gabra et al. (2022). While an intuitive recommendation would be to promote earlier termination in order to preserve soil water storage, Gabra et al. (2022) showed that the impact on subsequent cash crop yield is not straightforward. Additional studies are therefore needed to better understand how spring water depletion interacts with subsequent crop performance under Mediterranean conditions.

Soil water storage dynamics

During the summer cover crop period (07/08 to 13/10), irrigation treatments had little effect on overall soil water storage (fig 1a), which remained close to minimum values throughout the experiment, suggesting that nearly all water supplied through rainfall or irrigation was rapidly consumed by the cover crop. Although differences were not statistically significant, distinct dynamics could still be observed between treatments. Under IR0, soil water storage remained relatively stable and about 20 mm above the minimum stock, possibly because with the absence of irrigation, CC experienced hydric stress which limited deep root development and restricted water uptake to shallow soil layers.

Before 19/09, soil water content on IR+ decreased over time and nearly reached the minimum level, a trend explained by ET values lower than ET0 (Figure 2), showing CC experienced water stress during this period. Afterwards, soil water content increased and stabilized around 20 mm above the minimum stock because irrigation then compensated for CC ET.

IR treatment also depleted soil water reserves, but to lower levels than IR0 and IR+ until minimum stock was reached. This suggests that the establishment irrigation may have promoted deeper root development and access to deeper soil water reserves than IR0.

Overall, these observations suggest that irrigation management may strongly influence root development and access to soil water.

During winter, substantial rainfall rapidly erased initial differences in soil water storage between treatments, suggesting that the legacy effect of summer irrigation management was largely buffered under wet winter conditions. However, such legacy effects may persist longer under drier climatic conditions, highlighting the importance of considering temporal water flux dynamics when evaluating cover crop impacts on field-scale water balance.

Irrigation water productivity and management implications

Our study shows that irrigation water productivity was approximately twice as high for the IR treatment compared with IR+. This suggests that the establishment irrigation was particularly efficient, whereas the additional irrigations applied under IR+ were likely far less productive. From an operational perspective, this finding is particularly important in water-scarce Mediterranean regions. A strategy based on limited irrigation at sowing may represent a promising compromise between maintaining ecosystem service provision and preserving scarce summer water resources. Such an approach could help secure cover crop establishment under highly uncertain climatic conditions while limiting irrigation demand.

CONCLUSION

This study provides new insights into the temporal dynamics of soil water balance under irrigated cover cropping systems in Mediterranean conditions by jointly analysing soil water storage, cover crop water use and biomass production. Our results show that maximizing summer cover crop biomass production is highly water-intensive, with up to 180 mm of water consumed, including 150 mm supplied through irrigation. In contrast, the establishment irrigation treatment appeared to provide the best water use efficiency, suggesting that limited irrigation may already be sufficient to ensure cover crop establishment and provide ecosystem services such as erosion control.

Our results also highlight the importance of dynamically monitoring soil water balance processes in order to derive relevant agronomic recommendations, particularly regarding the risk of soil water depletion at the end of winter and the optimization of cover crop termination date. These findings remain to be confirmed across multiple experimental years but already raise new questions regarding a possible priming effect of irrigation on root development and the capacity of cover crops to access deeper soil water resources.

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