

AGROECOLOGICAL SOIL MANAGEMENT IN VEGETABLE PRODUCTION, IMPACT ON SOIL HEALTH AND IRRIGATION SCHEDULING

GESTION AGROÉCOLOGIQUE DES SOLS DANS LA PRODUCTION MARAÎCHÈRE, IMPACT SUR LA SANTÉ DES SOLS ET LA PROGRAMMATION DE L'IRRIGATION

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ABSTRACT

In Mediterranean conditions, irrigation is unavoidable to secure vegetable production. A major challenge is to maximize the conservation of plant-available water in the soil profile. Improving soil multifunctionality, especially water infiltration and retention, through agroecological practices like mulching and/or reduction of soil tillage could be efficient over time. The impacts of such soil conservation practices on the amount of plant-available water and its dynamics are not consistent and vary with soil texture. Soil management in market gardening can be fairly intensive, with several crops per year and repeated tillage operations. We set up a field experiment in 2023 at the INRAE experimental facility (Alénia, South of France), based on a gradient of soil management practices combining soil tillage intensity and organic matter (OM) supply. (*T-ref*: conventional tillage + low OM; *T-NA*: passive tillage + low OM; *TNA-Sup*: shallow passive tillage + high OM; *NT*: No tillage + high OM). Soil water dynamics was continuously monitored with both tensiometers and soil water content sensors. Once a year soil health was evaluated and water consumption and crop performances measured across seasons. After 2 years of experiment, we observed differences between treatments for soil conditions, irrigation schedule and amount of water supplied varied according to the crop species and to the treatment in such case. Data based on soil volumetric water content and water potential appeared less variable in the *NT* treatment compared to *T-ref* and *T-NA*, highlighting a potential buffering effect. *NT* exhibited the highest water infiltration rates across years and *T-NA* the lowest. For spring crop, total water amount could be similar between treatments but effective irrigation scheduling was different (cucumber) or cumulative water consumption was higher under *T-ref* (bell pepper). Our results highlighted the capacity of alternative, agroecological soil management in vegetable production to perform as well as conventional management, while improving soil health over time.

Keywords: Agroecological practices; Soil management; Irrigation schedule; Water consumption; Soil health.

RESUME

Dans les conditions Méditerranéennes, l'irrigation est inévitable pour assurer la production maraîchère. L'un des principaux défis à relever est de maximiser la conservation de l'eau disponible pour les plantes dans le profil de sol. L'amélioration de la multifonctionnalité du sol, notamment en matière d'infiltration et de contrôle de l'eau, grâce à des pratiques agroécologiques telles que le paillage et/ou la réduction du travail du sol, pourrait s'avérer efficace avec le temps. Les effets de ces pratiques de conservation des sols sur la quantité de l'eau disponible aux plantes et sur sa dynamique ne sont pas constants et varient selon la texture du sol. La gestion des sols en maraîchage peut être assez intensive, produisant plusieurs récoltes par an et des exploitations répétées de travail du sol. En l'an 2023, nous avons mis en place une expérience de terrain menée au centre expérimental de l'INRAE (Alénia, sud de la France), basée un gradient de pratiques de gestion des sols combinant l'intensité du travail du sol et l'apport de matière organique (MO). (*T-ref* : travail du sol conventionnel + faible teneur en MO; *T-NA* :

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travail du sol passif + faible teneur en MO; TNA-Sup : travail du sol passif superficiel + teneur élevée en MO; NT : sans travail du sol + teneur élevée en MO). La dynamique de l'eau dans le sol a été surveillée en continu à l'aide de tensiomètres et de capteurs de teneur en eau du sol. Une fois par an, la santé des sols a été évaluée et la consommation d'eau ainsi que les rendements des cultures ont été calculés au fil des saisons. Après deux années d'expérimentation, nous avons constaté des différences entre les traitements en ce qui concerne l'état des sols, la programmation de l'irrigation et la quantité d'eau fournie, qui variaient en fonction de l'espèce cultivée et du traitement appliqué. Les données concernant la teneur en eau volumétrique du sol et le potentiel hydrique se sont révélées moins variables dans le traitement NT que dans les traitements T-ref et T-NA, ce qui met l'accent sur l'effet tampon potentiel. Le traitement NT a présenté les taux d'infiltration d'eau les plus élevés sur l'ensemble des années, tandis que le traitement T-NA a affiché les plus faibles. En ce qui concerne les cultures de printemps, la quantité totale de l'eau pouvait être similaire entre les traitements, mais la programmation d'irrigation efficace était différente (concombre) ou la consommation cumulée de l'eau était plus élevée dans le cadre du traitement T-ref (poivron). Nos résultats ont mis l'accent sur la capacité des pratiques alternatives et agroécologiques de la gestion des sols dans la production sur maraîchère à offrir des performances équivalentes à celles des pratiques de la gestion conventionnelle, tout en améliorant la santé des sols au fil du temps.

Mots-clés : Pratiques agroécologiques; Gestion du sol; Programme d'irrigation; Consommation d'eau; Santé du sol.

INTRODUCTION

Vegetable production is characterized by intensive management, including frequent and intensive tillage, significant inputs of fertilizers and water and small OM restitution through crop residues (Lu *et al.*, 2021). In organic production the use of tillage is particularly justified given that the use of pesticides and herbicides is prohibited for weed, pest control and cover crop management (Bietila *et al.*, 2017). Tillage can directly affect physical, chemical and biological properties of soil, through modification of soil structure, SOC distribution and functional diversity in the soil profile for instance (Van Capelle *et al.*, 2012). This management can lead to decline in soil health, particularly regarding nutrient imbalances and soil aggregation with potential increasing in soil erosion under certain pedoclimatic conditions. For instance, Lu *et al.* (2021) showed a substantial decline in SOC (-25 %) and total N content over the 10 years following the transition from a paddy-rape rotation to open-field vegetable production, due to low inputs of crop residues and high tillage frequency. Climate change, characterized by more frequent extreme weather events such as high temperature, drought and heavy rain events can accelerate soil degradation. Under these conditions, the use of irrigation is becoming increasingly unavoidable. In south of France, the scarcity of water during summer months could lead to a reduction in water inputs for agricultural purposes. Reducing tillage intensity is identify as a key strategy to mitigate soil degradation (Hefner *et al.*, 2026). Its role in climate mitigation is more controversial, recent literature highlighted its role in vertical distribution of SOC more than higher SOC storage when depth is taken into account (Ferchaud *et al.*, 2025). Reduced tillage combined with cover crops and diversification (conservation agriculture) are often promoted to improve the usable water storage functioning, through improved water infiltration and water retention but literature is not consistent and results are very pedoclimatic context dependent (Bescansa *et al.*, 2005, Kool *et al.*, 2019, Li *et al.*, 2015). However, results based on runoff and soil erosion are more consistent and showed significant improvement that can be notably related to the aggregate stability (Palm *et al.*, 2014). While reduced tillage practices are intensely studied in field crops, it remains poorly studied in vegetable production (Davis *et al.*, 2022). Comparison is also valuable for the implementation of practices by growers, as vegetable production is characterized by high-values crops production and smaller land areas, mitigate the risk is challenging (Hefner *et al.*, 2026). Moreover, experimental setup in vegetable production can be differ significantly from actual production condition. In vegetable production, reduced tillage can be implemented through the reduction of depth of tillage, the use on non-inversion tillage, located non-inversion tillage such as strip-tillage and strict no-till system. Potential reduction of porosity due to soil compaction (particularly at the beginning of implementation and dependent of the stage in no-till conversion) in no-till systems can be partially counteracted by the addition of OM and so macrofauna activity that could induce stable bioporosity

(Capoweiz *et al.*, 2009). No-till practices associated with high inputs of mulch through compost or green waste shredding, known as “Maraichage sur Sol Vivant” can reached 200 t. ha⁻¹ at a time (Faury, 2020). In a recent study in north of France, Langard *et al.* (2024) showed through multicriteria analysis that this kind of practices can induced nitrate leaching into groundwater highlighting the need for furthers experimental research on these practices. This study aims to compare four soil management practices according to soil tillage intensities combined with varying amounts of exogeneous organic carbon, in terms of their effects on soil functions. Particular attention is given to soil parameter related to soil water dynamics e.g., water retention, infiltration, and soil compaction – as well as to irrigation schedules and their effects on crop yields and water productivity. Water use efficiency was also evaluated on spring crop, based on sap flow measurement (Mathieu *et al.*, ICID 2026)

MATERIELS AND METHODS

Study site and experimental design

The experiment was conducted at the INRAE Experimental Facility in Alenya, France beginning in spring 2023 and will conclude in August 2026, in a Mediterranean climate. The soil type was a fluvisol characterized by a deep loamy-silty texture, which has been farmed organically since 2023. The experimental design consisted of 4 treatments, based on different intensities of tillage and two different amounts of organic matter. Specifically, the NT treatment was characterized by strict no-till and high amount of organic matter inputs; TNA-Sup by passive and shallow tillage (0-15cm) with high amount of organic matter inputs; T-NA by a passive tillage and low amounts of organic matter inputs; and T-ref by conventional tillage and low amounts of organic matter inputs as mainstream producer practice (Système Maraicher Avec reduction du Travail du Sol : SMART-Sol, **Figure 1**). It's important to notice that current NT and TNA-Sup plots have been both conducted under no-till between the end of 2019 and 2023 (non-project framework). Both have received 95 t. ha⁻¹ of green waste shredding in 2019, incorporated in TNA-Sup and leave on the surface in NT. Others inputs of green waste shredding was done in 2022 (60 t. ha⁻¹) and inputs of compost in 2020 (200 t. ha⁻¹) and 2024 (100 t. ha⁻¹). TNA-Sup was reverted to reduced-tillage in 2023. T-ref and T-NA treatments received 30 t. ha⁻¹ of compost in 2024. Each treatment was conducted in an unheated 320 m² plastic tunnel, which was a standard size for vegetable production in the region. The side borders were excluded from the experimental sampling area, thereby reducing the total area of the experiment to 213 m². Each plot was divided in 5 interleaved subplots, which were treated as pseudo replicates for data analysis.

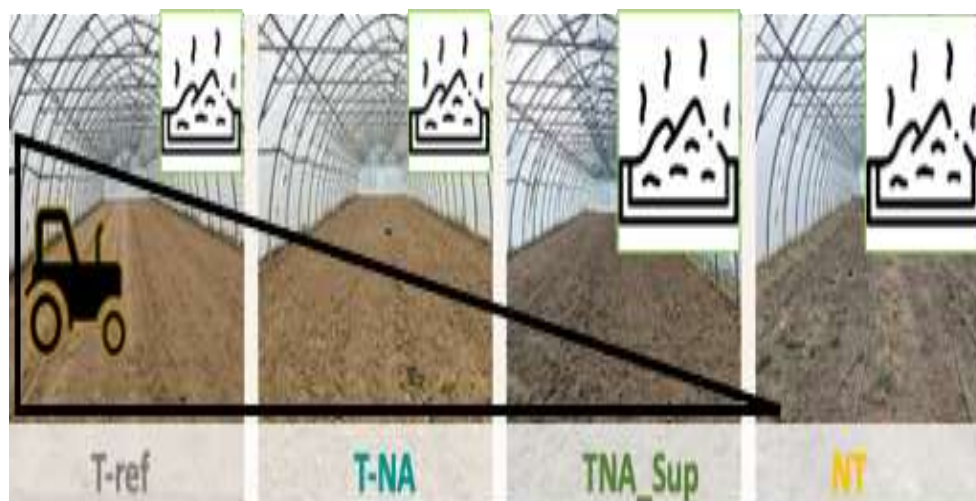


Figure 1. Simplified diagram of the experimental device ‘SMART-Sol’

Crop management

Over the course of the experiment, the crop rotation was as follows: cucumber, sorghum, lettuce, bell pepper, kohlrabi, tomato, solarization, fennel. The results presented here concerned the first 2 years of cultivation. Irrigation was managed on a weekly basis, relaying on both readings from tensiometer and human expertise gained through plant observation and soil core samples taken once or twice a week. For spring crops, irrigation was controlled using the following formula:

$$\text{irrigation rates} = K_c * ET_0$$

Where irrigation rates were the amount of water to bring in mm, K_c is the crop coefficient and ET_0 is evapotranspiration in mm. Crop fertilization was carefully managed based on residual soil nitrogen and plants' needs. Plastic mulch was used to avoid weed growth. Volumetric irrigation measurements were recorded at each irrigation event to determine the irrigation schedule and total volume per crop cycle.

Soil volumetric water contents and soil water potential monitoring

Soil volumetric water content (VWC) was measured every 30 sec using CS 650 TDR probes (Campbell Scientific, Inc., Logan, UT, USA) at depths of 10cm and 30cm ($n = 3$). Laboratory calibration was performed according with standard (Giot and Cousin, 2012; Giot, 2016). Soil water potential was recorded using watermarks every 15 min at both 10 and 30cm depths ($n = 7$). The drip irrigation lines were equipped with capillaries to place the probes between 2 drippers an ensure no variation between data acquisition zones.

Soil measurements

Soil bulk density was determined using method that measures mass after oven drying. Undisturbed soil core samples were collected at 10 and 30 cm soil depths using a bulk density auger kit (SDEC France, Tauxigny, France). Measurements were taken during 8 fields campaigns conducted during the crop growing seasons between 2024 and 2026. Three soil cores were collected by depth and per treatment at each sampling date. Soil water infiltration was measured using the Beerkan method adapted according to the Biofunctool® method (Thoumazeau *et al.*, 2019). The ring was installed with a plant cut at the base in its center. The time required for the total infiltration of a 33 cl volume into a 20 cm diameter ring (simulating 1 mm of irrigation) was recorded rounded to the nearest second. The water stability of the soil aggregates was determined using the slake test method (Herrick *et al.*, 2006) adapted with the Biofunctool® method.

Marketable yield assessment and water productivity

The mature vegetable biomass was harvested on selected plants (this number varied depending on whether the crops were winter or spring crops) within each subplot. For winter crops, the plants were weighed and counted one by one, for spring crops an average weight was calculated based on the sum of the weights and the total number of fruits counted. For winter crops, harvesting was carried out on a single date, the first treatment to reached maturity triggered the harvesting of the others. Yield results are expressed as number of fruits, crop weight (kg.m^{-2}) of gross biomass and marketable fruits. Water productivity was expressed in kg of fruit per mm of applied water.

Data analysis

All statistical analyses were performed using Rstudio (2025.05.0+496). Permutation test ($n = 500\ 000$) of Monte Carlo was computed to determine within a cultural cycle if differences exist between treatments. Post hoc tests were performed through pairwise comparison, with p-adjusted value (Benjamini-Hochberg correction).

RESULTS AND DISCUSSION

Irrigation schedule

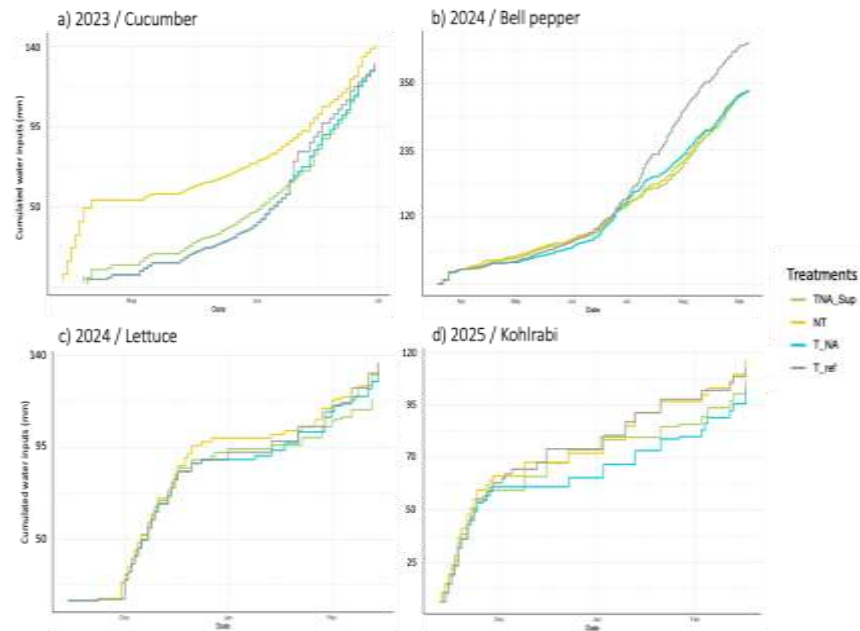


Figure 2. Irrigation schedule over time for a) cucumber, b) bell pepper, c) lettuce and d) kohlrabi

At the beginning of the study in 2023, a drip irrigation of 46 mm spread over 6 days prior plantation was necessary to facilitate the digging of planting holes for the cucumber in the NT treatment, because of high soil density feeling (**Figure 2**). Until harvest, the T-ref, T-NA and TNA-Sup treatments followed the same irrigation curve. A slight decrease of irrigation for T-ref was then observed during the harvest period. Water supply gradually increased in the NT treatment until it reached the levels of the other treatments by the end of the growing season. At the end of cucumber growing season, the cumulative water supply was fairly across treatments, i.e., from 129 to 141 mm over 77 days. During the 93-days of growing period for lettuce, the irrigation management and schedule were fairly similar across the different treatments. A slight increase of water provision was observed in the NT treatment in January, which was surpassed by the T-ref and T-NA treatments by the end of the period.

The TNA-Sup treatment highlighted slightly less water supply (151 mm) compared to all others treatments (ranging from 179 to 192 mm). For bell pepper cultivation, 20 mm of water was applied in all treatments to facilitate planting. All treatments followed the same irrigation schedule until start of harvest, thereafter, the T-ref treatment required a greater water amount. Ultimately, the total amount of water supplied amounted to 425 mm for the T-ref treatment and approximately 340 mm for all others treatments across 171 days. Kohlrabi cultivation (97 days) required nearly 110 mm, regardless the treatment (**Figure 2**).

Overall differences in the irrigation management were observed between treatments only for the spring crop, both in terms of irrigation schedule and the tendency to increase water application in the T-ref treatment. These results will be need to further investigated in future growing seasons. After 2 years of cultivation, irrigation management appeared more flexible in the NT treatment compared to T-ref. More precisely, during spring crop, irrigation intervals were better managed under the no-till practice.

Soil water potential profiles

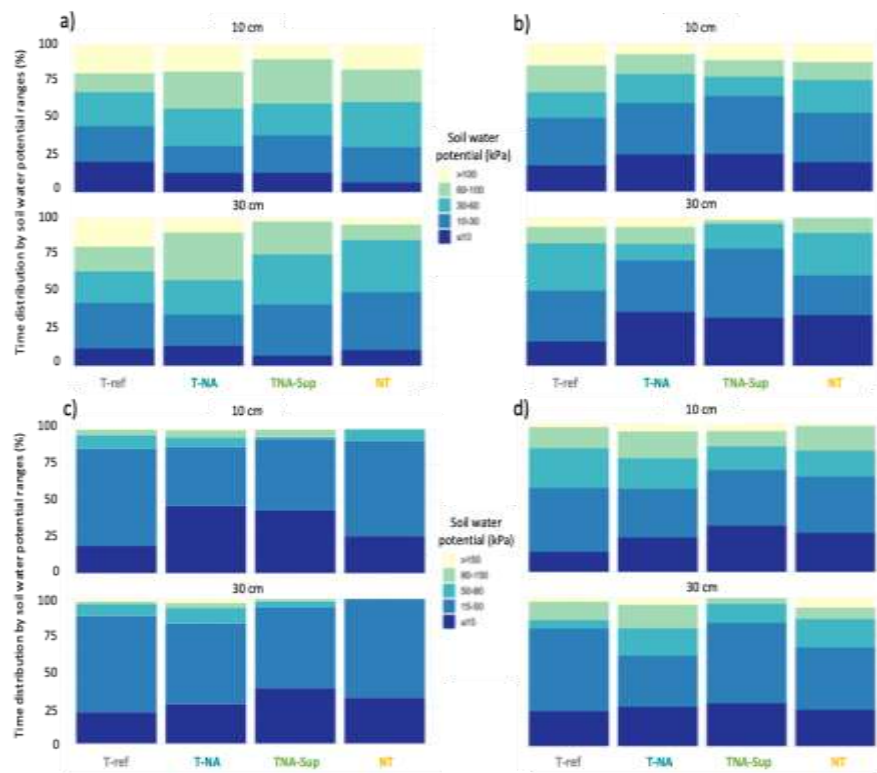


Figure 3. Frequency distribution (based on daily median) of the time spent in different soil water potential classes per treatment and soil depth during crop cycle for a) cucumber, b) bell pepper, c) lettuce and d) kohlrabi (n=7)

For the T-ref and T-NA treatments, the soil profile under cucumber was fairly similar at both depths of 10 and 30 cm, indicating similar fluctuations of water availability in these treatments while for the TNA-Sup and NT treatments, the profile was more consistent at 30 cm depth (**Figure 3 a**). At this depth water appeared to be more available (from > 10 to 60 kPa) in the TNA-Sup and NT treatments whereas more time was spent in the range of 60 to > 100 kPa in the T-ref and T-NA treatments. It was quite interesting because the total water supply was fairly similar between different treatments.

This could indicate a buffering effect soil layers under no-till conditions, although evidence of improved water retention in no-till systems is inconsistent (Alletto and Bustillo, 2023). For bell peppers, the soil profile pattern was fairly similar across treatments at depth of 10 cm. At 30 cm depth nearly 25 % of time saw values below 10 kPa for the T-NA, TNA-Sup and NT treatments indicating potential useless water for plant uptake (**Figure 3 b**). Interestingly even if the T-ref treatment received 70 mm more water than the others treatments, the soil profile did not show a higher amount available water at the crop scale. This could be related with greater water use by the bell pepper for fruit production.

During winter, particularly for lettuce growth, soil profile exhibited high soil water availability at both depth of 10 and 30 cm, with more than 75 % of time spent in soil water potential < 50 kPa (**Figure 3 c, d**). TNA-Sup treatment which received the less amount of water did not show less available water than others treatments. Buffering effect of no-till soils also seems to be visible for lettuce, at a depth of 30 cm (100 % of time spent < 50 kPa).

Soil volumetric water content profiles

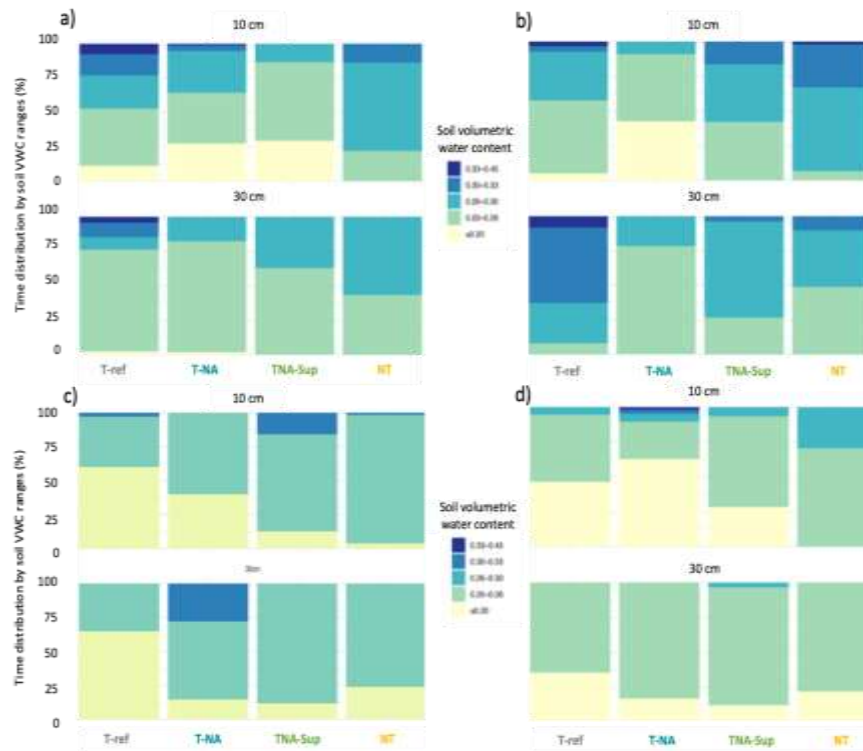


Figure 4. Frequency distribution (based on daily average) of the time spent in different soil VWC per treatment and soil depth during crop cycle for a) cucumber, b) bell pepper, c) lettuce and d) kohlrabi (n=7)

Data obtained with TDR probes showed more stable pattern than those translating water availability obtained with soil water potential sensors. Soil VWC profile was very dependent of the cultivated specie with more differences between treatments during spring crops. During cucumber cultivation, the T-ref treatment exhibited the greatest variability in VWC over time and across depth. As for soil WP, soil VWC appeared more variable at a depth of 10 cm compared to 30 cm, particularly for all alternative treatments (**Figure 4 a**).

Under the T-ref treatment, frequent irrigation early in the growing season led to high VWC at the soil surface, which could be related to high soil porosity, as the soil can saturated with water immediately after tillage (Bodner *et al.*, 2013). For bell peppers, the T-ref and T-NA treatments exhibited similar pattern of VWC dynamics, with fairly rapid increase in VWC at depth in first time, but with wetter soils under the T-ref treatment (data not shown). Over the course of the growing season, it was evident that the VWC at 30 cm depth under T-ref differed significantly from other treatments, with nearly 50 % of time spent at field capacity because of the + 25 % of water supply. During winter crops T-ref and T-NA appeared drier among crop cycle in the surface, while soil WP profile was fairly similar between treatments (**Figure 3 c**).

This could indicate that for the same water potential, no-till soils contain more a higher volume of water and could reach permanent wilting point latter (Blanco-Canqui and Ruis, 2018). One particularity in NT was that curves at depth of 10 and 30 cm were very close and follow the same trend of pattern, without ever crossing paths while it often happened under other treatments (data not shown).

Water infiltration

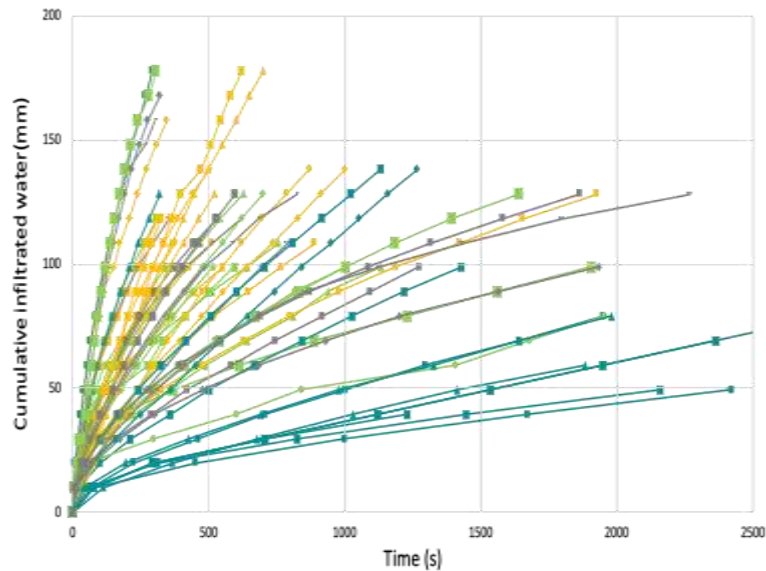


Figure 5. Water infiltration rate across years (2023; 2024; 2025) for T-ref (grey lines), T-NA (blue lines), TNA-Sup (green lines) and NT (yellow lines).

Over the course of the 3 years, water infiltration rates tend to show 3 groups. The T-NA treatment exhibited the lowest infiltration rates across all years while NT recorded the highest rates (**Figure 5**). T-ref and TNA-Sup treatments exhibited both rapid and slow infiltration rates, regardless of the year of measurement. This may highlight the high spatial heterogeneity caused by reduced tillage, whatever the amount of organic matter added. Indeed, reduced tillage consist in passive chisel that can create coarse condition, with clods rather than fine soil layer as with animated tillage.

Soil water stability

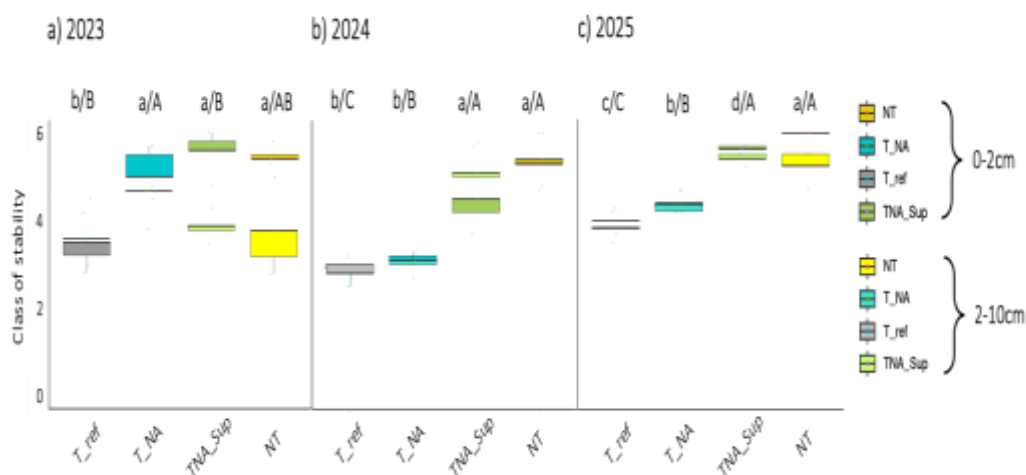


Figure 6. Box plot representing classification for soil water stability in 2023 (a), 2024 (b) and 2025 (c) depending on treatment and soil layers (0-2 cm or 2-10 cm). Lowercase letters indicate statistical group differences between treatment within 0-2 cm depth and capital letters indicate it for the 2-10 cm depth, for each year (n = 5).

Within the topsoil layer (0-10 cm), the addition of significant amounts of organic matter combined with reduced-till or no-till practices significantly improved soil water stability over the years (**Figure 6**). Depending to the year, soil water stability can be improved until 33% with samples achieved the highest rating in the classification for NT (**Figure 6 c**) and TNA-Sup (**Figure 6 a**). Overall, soil water stability showed low variability, regardless of depth or the treatment. However, aggregates in the surface layer (0-2 cm) exhibited the highest water stability for TNA-Sup and NT in 2023, compared to the sub-surface layer (2-10 cm).

In 2024 and 2025 no difference was observed between the surface and sub-surface layers for TNA-Sup and NT, which could indicate a homogenization of the soil structure across depth. In their meta-analysis, Norris and Congreves (2018) showed that in alternative management of vegetable production systems, soil health indicators such as aggregate stability was often improved without being able to distinguish the effect of practices (cover crop, reduce tillage, amendments).

Soil bulk density

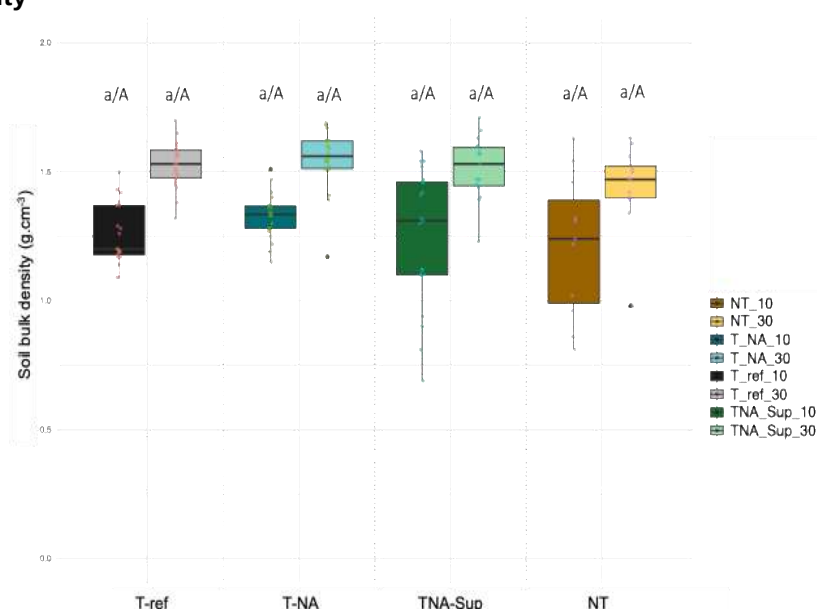


Figure 7. Soil bulk density at a depth of 10cm (dark symbols) and 30cm (clear symbols) depending on treatment. Lowercase letters indicate statistical group differences between treatment at 10cm depth and capital letters indicate it for 30cm depth, (n = 24).

The topsoil layer (10cm) was characterized by the lowest soil bulk density, regardless of the treatment (**Figure 7**). The TNA-sup and NT treatments exhibited greater variability, it might be due to high macrofauna activity at the surface and consequently higher porosity (particularly through visible earthworm's burrows). Combined with high OM content this could result in an apparent bulk density $<1.0 \text{ g.cm}^{-3}$ in certain areas. No significant difference was detected between treatments at 30cm depth, with values ranging around 1.5 g.cm^{-3} . While soil compaction is often observed in no-till practices during field trials, on small surface vegetable production, tractor is used only for planting preparation and the application of OM; all other agricultural tasks are done by hand.

This could explain the lack of observed differences. Another explanation could be related to the date on which the soil samples were collected, the bulk density of soil was measured at different stages after soil tillage which could introduce variability because of redensification of the soil, that could mask the differences (Osunbitan *et al.*, 2005, Kool *et al.*, 2019)

Marketable yields and water productivity

The results of the Monte-carlo permutation test revealed a significant overall difference between treatments for cucumber ($p=0.018$), bell pepper ($p=0.004$) and kohlrabi ($p=0.008$), while no significant difference was observed for lettuce ($p=0.062$) (**Figure 8**). During cucumber trial, although the post-hoc test detected no significant differences between treatments ($p\text{-adjust} > 0.05$), the range of certain permutation statistics (-1,90 to 2,04) indicated that T-NA tended to be less productive than other treatments (4.7 kg.m⁻² vs 5.8 to 6.8 kg.m⁻²). For bell peppers, significant lower yields were observed in TNA-Sup (3.3 kg.m⁻²) compared to T-ref (5.9 kg.m⁻²) and NT (5.0 kg.m⁻²) (**Figure 8**).

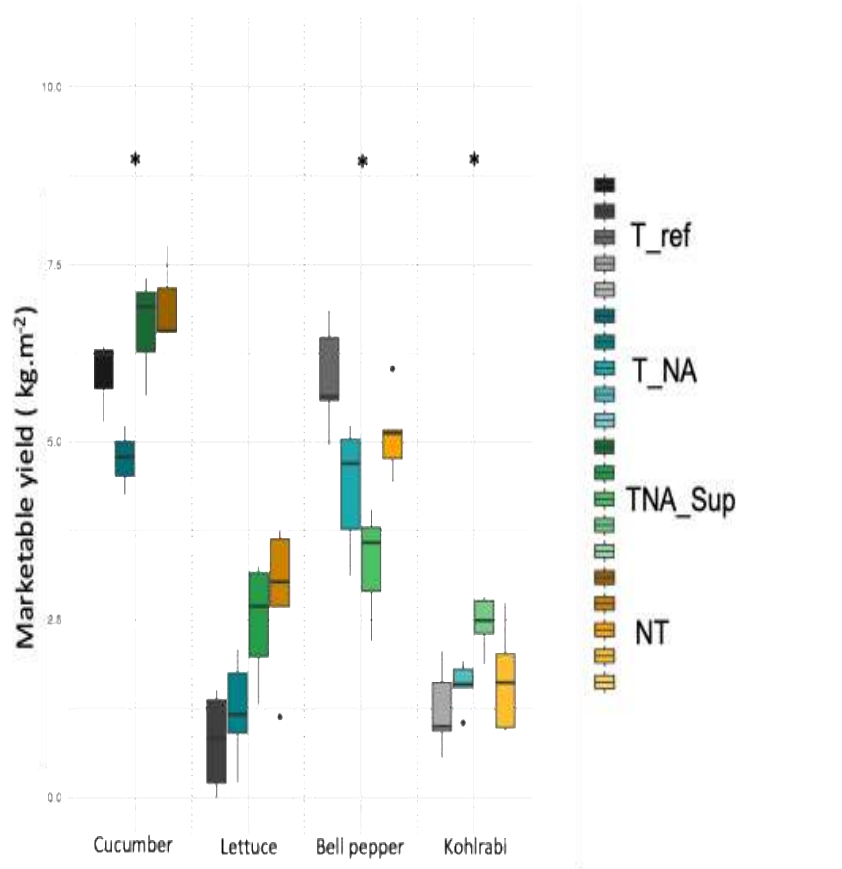


Figure 8. Marketable yield over time for different treatments and crop species, (*) indicate significant overall Difference between treatments for one specie (n = 5).

Lettuce yields ranged from 0.78 kg.m⁻² in the T-ref treatment to 2.8 kg.m⁻² in the NT treatment, with high variability among treatments and no significant difference ($p = 0,062$). A pairwise comparison was nevertheless conducted for exploratory purposes and showed tendency to distinguish TNA-Sup + NT from T-NA + T-ref (p -values ranging from 0.057 and 0.066). This trend was related to the harvest date. The experimental setup had been designed such that the first treatment ready for harvest triggered the harvest of all the others. This resulted, in this case, in lettuce sizes that did not meet marketing standards in T-ref and T-NA treatments.

Data on early growth, based on the number of leaves were across all treatments, indicating that a slight differentiation emerged later. Kohlrabi showed fairly close yield values ranging from 1.43 to 3.50 kg.m⁻² in average. In vegetable production, one of the concerns associated with no-till is delayed early development, as the soil may warm up more slowly, particularly in the spring. In the experiment, the temperature at a depth of 10 cm generally highlighted less variation in the NT treatment compared to all

others treatments. This resulting in a higher minimum temperature in winter and a lower maximum temperature lower in summer. Heat accumulation in the no-till soil during summer resulted in warmer soil for planting winter crops and during the first weeks of growth, while it resulted in cooler soil at the start of summer crop growth. Water productivity followed the same trend as marketable yields for cucumber, lettuce and kohlrabi as total amount of water was similar between treatments. For bell pepper even though marketable yield was slightly increased in T-ref, when it's normalized by amount of water, water productivity showed no further difference between treatments, indicating that water was not more valorized in fruit production.

CONCLUSION

Alternative soil-management practices, compared with conventional maintained fairly similar marketable yields for cucumber, lettuce and kohlrabi, while bell pepper was slightly reduced. When expressed through the amount of water applied, the water productivity of cucumber and lettuces tended to be improved in the TNA-Sup and NT treatments while no significant differences were observed for bell pepper and kohlrabi. Soil health function such as maintain of soil structure and water infiltration were enhanced by no-till combined with high amounts of OM. The buffering effect of NT and TNA-Sup (< 10 cm) on soil water dynamics was evident particularly on soil WVC, although a modest effect on the soil WP was also detected. We acknowledge that the use of plastic mulch in all treatments may have buffered or masked potential negative effect of the lack of tillage (e.g., weed control and reduced soil warming that could accelerate crop development). Further experiments are required to investigate a broader range of pedoclimatic conditions and responses of different crops.

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